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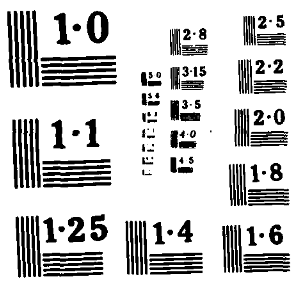
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SPECIAL COURSE ON

CRYOGENIC TECHNOLOGY FOR WIND TUNNEL TESTING

The material assembled in this publication was prepared under the combined sponsorship of the Fluid Dynamics Panel, the von Kármán Institute and the Consultant and Exchange Program of AGARD and was presented as an AGARD Special Course at the von Kármán Institute, Rhode-Saint-Genèse, Belgium, 22—26 April 1985.

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PREFACE

As noted by Dr Goodyer in the Preface to AGARD Lecture Series 111, Cryogenic Wind Tunnels, the advantages of the cryogenic tunnel for aeronautical research lie mainly in the practical attainment of full-scale values of Reynolds numbers and in the case of pressurized cryogenic tunnels, the means to separate Mach number and Reynolds number effects from aeroelastic effects.

Since 1980 the advantages of cryogenic tunnels noted by Goodyer have been demonstrated to be valid. The continued interest in cryogenic tunnels has promoted a second series of lectures devoted to the topic. Since LS 111 there has been a subtle shift in interest away from some of the major concerns of 1980, e.g. real-gas effects, toward concerns more directly related to the application of cryogenic tunnels. The content of this present series of lectures has been selected to reflect this shift in interest.

It has been demonstrated that large cryogenic tunnels can be built and successfully operated. We now ask, is it possible to build models for cryogenic tunnels, test them, and get data of sufficient accuracy so that the advantages of testing at full-scale values of Reynolds number are realized?

This ~~Special Course~~ addresses this question. It is specifically designed for those who wish to acquire in concentrated form the most up-to-date information on the principles and practices of cryogenic wind tunnel design, operation, and application.

Following a brief review of the development and early application of cryogenic wind tunnels, all of the aspects of cryogenic wind tunnel technology related to the design and operation of cryogenic tunnels are examined. Among the areas covered are: cryogenic engineering and safety, properties of materials at cryogenic temperatures, model design requirements and fabrication techniques, instrumentation for control and data acquisition, data accuracy, productivity, and costs of models and operation.

A review of the status of the cryogenic wind tunnel projects in AGARD countries and in the rest of the world is presented.

This Special Course is sponsored by the Fluid Dynamics Panel of AGARD and implemented by the von Kármán Institute.

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INTRODUCTION TO CRYOGENIC WIND TUNNELS

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SUMMARY

The background to the evolution of the cryogenic wind tunnel is outlined, with particular reference to the late 60's/early 70's when efforts were begun to re-equip with larger wind tunnels. The problems of providing full scale Reynolds numbers in transonic testing were proving particularly intractible, when the notion of satisfying the needs with the cryogenic tunnel was proposed, and then adopted.

The principles and advantages of the cryogenic tunnel are outlined, along with guidance on the coolant needs when this is liquid nitrogen, and with a note on energy recovery. Operational features of the tunnels are introduced with reference to a small low speed tunnel.

Finally the outstanding contributions are highlighted of the 0.3m Transonic Cryogenic Tunnel at NASA Langley Research Center, and its personnel, to the furtherance of knowledge and confidence in the concept.

1. BACKGROUND

In any attempt to justify the expenditure of considerable manpower and effort on a project such as that forming the subject of this Series it is necessary to reflect for a moment on the underlying reasons for the work, which I will first attempt to do. The root cause of us all being here is the fundamental weakness of classical mathematics: despite the undoubted brilliance of mathematicians past and present they have not been able to give us the means to forecast by calculation, and with certainty, the behaviour of real life devices of the kind represented by the products of aerospace industries. This failure reveals inadequacy in the discipline and not in the practitioners. A quotation specifically about our business of aerodynamics is as follows: "The disparity between the designer's need for aerodynamic prediction and the power of his analytic methods seems to be so vast as almost to defy description."[1] This statement was published by a most experienced aircraft designer in September 1971, close to the time of the beginning of construction of the first cryogenic wind tunnel.[2] Since then the two avenues of endeavour, empirical and theoretical, have advanced in healthy competition with improvements in each, which is a recognition that the former was not without weakness.

The birth of the cryogenic wind tunnel was preceeded by a 20 year period spawning almost all of the transonic wind tunnels now in use. During this period the need to provide for the needs of experimental aerodynamics in a reasonably economic way followed the pattern already set, that of matching the required Mach number but not the required Reynolds number. The reason for this is that Mach number effects were known to be strong while it was felt that the effects of Reynolds number on performance were rather weak and perhaps systematic and predictable. If the same circumstances existed now and we had to choose between the two parameters there is no doubt that we would still pick Mach number for proper matching. It is perhaps fortunate that background research in Japan and the U.S.A. in the 1930's allowed the development of the ventilated test section for transonic testing, satisfying the immediately most pressing needs at reasonable cost. Had Reynolds number effects seemed more important there is no knowing what solutions might have emerged, but quite likely the cryogenic wind tunnel, because the necessary information and technology was around and the route to satisfying Reynolds number by more conventional means is inordinately expensive.

It should be mentioned that throughout almost the whole course of aerodynamic testing, the position with regard to Reynolds number was not accepted without question. The needs of the low speeds of the early days of flight were satisfied with large unpressurised wind tunnels which were just economically feasible, but the situation became more difficult with the progressive increases particularly in airspeed but also in aircraft size. To anyone who begins to design a wind tunnel for flight values of Reynolds number at normal values of tunnel pressure and temperature it soon becomes apparent that the cost will be very high. To circumvent this problem searches were made, from about 1920 onwards, for test gases alternative to air which would inherently provide such flows at reasonable size and cost (Pozniak[3] contains a comprehensive summary and list of references). The searches revealed some gases which were not too toxic and which would provide useful increases in Reynolds number, by factors of up to 4 when compared with air at otherwise the same conditions. However these gases were polyatomic with ratios of specific heats γ much lower than in air and it was felt that for testing at compressibility speeds their behaviour might not always be close enough to that of a diatomic gas. It is no use replacing one system which occasionally and unpredictably gives wrong answers (that is air at low Reynolds number) with another which might also do the same. Mixtures of gases having $\gamma = 1.4$ gave too small rewards.

On at least two occasions the prospects were discussed for the use of low temperatures in aerodynamic testing. Margoulis[4] in 1920 and Smelt[5] in 1945 published predictions of the advantages, but the possibilities were largely ignored although from time to time in reports from the period various authors again drew attention to the idea. It is likely that the motivation for producing high Reynolds number flows was not strong enough to encourage the facing of the practical problems.

While errors can be made of either sign in the prediction of aircraft performance, the cases which cause concern are those where full scale performance is worse than expectation by too large a margin. In the U.S.A. and Europe during the above period there were examples of aircraft projects which performed rather too badly in comparison with predictions based on wind tunnel data. The concensus was that mismatch in Reynolds number was the likely cause. From these experiences began compaigns on both sides of the Atlantic to provide transonic wind tunnels with Reynolds number capabilities closer to those experienced in flight, and there began considerable activity on the subject.

AGARD, through its Fluid Dynamics Panel, first set up the High Reynolds Number Working Group (HIRT) in 1969 which reported on some solutions to the transonic needs of NATO countries in September 1970. Following this the same Panel set up the Large Wind Tunnels Working Group (the LaWs Group) in 1971 to examine broader needs of aerodynamic testing but including those of transonic testing, and to evaluate the options, although the option of the cryogenic wind tunnel was not evaluated[6]. These activities represent an interim period, ending in about 1973, when a variety of solutions was actively persued based on the use of normal temperatures but often in otherwise unconventional wind tunnels.

Those involved first set out to define requirements and then to identify possible solutions. On the subject of requirements it should be mentioned that other inadequacies in flow simulation had also become apparent in the meantime, additional to that simply of low Reynolds number. Notable was the realisation that other measures of flow quality including non-uniformity, noise and turbulence, were often unsatisfactory and would need to be improved in any new wind tunnel. On the subject of the requirement for Reynolds number there were differences of opinion on the extent to which it was necessary to bridge the existing tunnel-to-flight gap. Some (mostly in Europe) felt that there was a level below which there could be expected to be seen changes in data and above which there would be no significant change. Others (mostly in the U.S.A.) felt that tunnels should match flight if at all possible.

There was also disagreement over the minimum practical run time for the new tunnels, but the consensus was that around 10 seconds would suffice for most kinds of test. However in retrospect there is no doubt that such compromises, including any proposed for Reynolds number, were forced by what was considered economically possible rather than being based on real technical merit.

The tunnel specifications which emerged included minimum run times, Mach number bands, maximum pressure and of course Reynolds number. In Europe it was recognised that this would need to be a multi-national collaborative project because of the capital cost. Several competing schemes emerged for evaluation[6]. A tunnel was separately proposed for the U.S.A. which also had several competing schemes[7,8,9].

Figure 1 compares the requirements of cruising flight with the Reynolds number capabilities of tunnels each side of the Atlantic. A representative selection of transport aircraft is shown, and it is apparent that tunnel capability is below flight by factors up to 5:1 in the case of larger transonic aircraft. (The picture has changed little in the meantime except for the case of the N.T.F. which is becoming available in the U.S.A.).

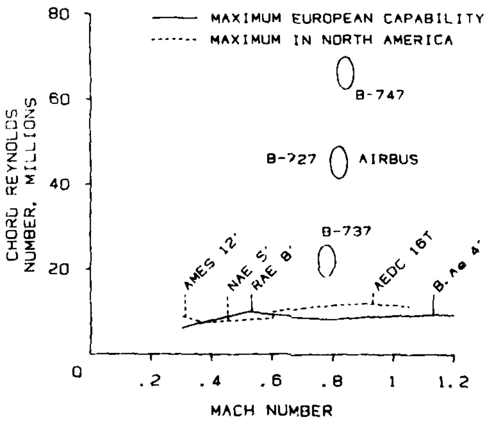

Figure 1: Maximum Reynolds numbers available each side of the Atlantic in conventional transonic tunnels, compared with requirements of some transport aircraft at cruise.

The projected cost of a tunnel varies strongly with its size and therefore all steps are taken to minimise size, including the use of the maximum practical pressure, but there are limits to the pressure that can be used. It is easy to show that in the case where the structure of an aircraft is modelled as well as the aerodynamic envelope, the bending stresses in the wind tunnel model, say in the wing root, in relation to those in the aircraft in flight are factored by the two ratios, tunnel-to-flight, of the static pressures and lift coefficients. The tunnels which offered the highest Reynolds numbers used static pressures several times those experienced in transonic cruising flight. Further, particularly in the case of transport aircraft, the range of lift coefficient required to be explored in the tunnel could be much wider than structurally acceptable in the aircraft. The net effect is that models are designed for high loads which demand the use of high strength materials (for example maraging steels) coupled with the use of much thicker sections in the model's structure compared with the aircraft, to the point of many components being solid. With increases in pressure there is an increasing problem arising from support interference. While these comments are on the subject only of stresses, aeroelastic considerations may be even more demanding in terms of model and support stiffness. It was clear that there was insufficient scope for raising Reynolds number to the levels required by the sole action of raising the test pressure.

The outcome was a set of designs featuring large test sections (typically 5m, 16 feet across) operating at pressures up to 5 atmospheres or more, with various kinds of intermittent drives. The combination of size and pressure resulted in tunnels projected at rather high cost and requiring also large and expensive models.

At about this stage (in fact in September and October 1971) a small group of people at NASA Langley Research Center were faced with a similar kind of problem in relation to a wind tunnel magnetic suspension and balance system, that is much too low a Reynolds number, and proposed the use of a low temperature gas as a means to raise the value. A low speed tunnel was immediately built which served to dispel the most elementry misgivings over the concept and also served to draw the attention of the teams working on the large transonic tunnel projects to this alternative approach. In due course the proposals for large transonic tunnels on both sides of the Atlantic narrowed to just the cryogenic wind tunnel, fan driven and therefore nominally continuous, capable of reaching full scale flight Reynolds numbers at moderate tunnel size and pressure.

The cryogenic wind tunnel evidently was born out of needs of transonic testing, but is finding wider application as we will hear in due course.

The decision to proceed with an investigation of the cryogenic approach for transonic high Reynolds number testing opened up many new lines of endeavour additional to that of just proving the novel aerodynamics. There were the subjects to address of tunnel design and control, instrumentation, real gas effects, safety, materials and model making. These and more were first taken on by NASA in relation to the fan driven tunnel. Other organisations have extended the range of tunnel drives, as we will hear later in the Series, to cover the familiar intermittent options as well as some novel drives devised to exploit the particular characteristics of cryogenics.

The aims of the remaining part of this paper are to introduce some principles, and this will be by reference to the simple underlying theories and also by reference to two early wind tunnels in order to highlight some design and operational features.

2. PRINCIPLES OF CRYOGENIC WIND TUNNELS

2.1 Fundamentals

While the ideas can be applied to almost any gas, with particular advantage in low speed testing where a wider range of possibilities opens up with the relaxation of a constraint on γ [10], in transonic tests where I believe we are constrained to using diatomic gases there is little if anything to be gained from gases other than air or nitrogen, which the following comments assume.

The basics can be introduced very simply by substituting into the Reynolds number expression

$$\text{Reynolds number } R = \frac{\rho V \ell}{\mu}$$

density ρ in terms of pressure and temperature T from the ideal gas equation of state, velocity V as the product Mach number and speed of sound, and viscosity μ by the approximation $\mu \propto T^{0.9}$. The advantage in terms of Reynolds number of cooling a gas may be conveniently written as a ratio, that is the ratio of the Reynolds number at reduced temperature T to that in the same gas at normal temperature T_1, other factors such as model size ℓ, flow Mach number M and pressure P remaining constant.

The resultant expression is

$$\text{Reynolds number ratio} = \left(\frac{T_1}{T}\right)^{1.4}$$

the value of the ratio depending on the choice of the higher temperature which might be typically about 320K in a continuous tunnel, and on the factors limiting the lower temperature. The lower limit is not necessarily completely defined. It depends on the test Mach number, on the equilibrium saturation boundary of the gas and therefore on the test pressure, but also on the amount of supersaturation permissible in the flow, which may prove to be size- or model-dependent. It should be mentioned that controlled levels of supersaturation have been exploited in hypersonic tunnels for years without adverse effects. During the life of the cryogenic wind tunnel the phenomenon has been the subject of research, because the rewards in terms of Reynolds number and in other respects can be quite useful. There is strong evidence that it is safe to approach the saturation boundary in the free stream ahead of the model. If this is adopted along with a Mach 1 test then the ratio takes the approximate maximum values

6.4 at 1 atmosphere stagnation pressure

5.0 at 5 atmospheres stagnation pressure.

In either case it can be seen that the factor is nicely in accord with the needs outlined in the preceeding section.

The issue of pressure should be discussed because it has been already in relation to other tunnels. A measure of the effect of test pressure on model aerodynamic loads is the dynamic pressure $\frac{1}{2}\rho V^2$, other factors such as Mach number, size and lift coefficient remaining constant. Similar substitutions as above lead immediately to the expression

$$\tfrac{1}{2}\rho V^2 = \frac{\gamma}{2}\, pM^2$$

showing that temperature does not affect dynamic pressure. Therefore the increase of Reynolds number which accompanies reduction of temperature is not at the expense of load, at least to a first order.

Particularly if the tunnel is to be driven by a fan there is interest in the influence of temperature on the required power. Fan drive power can be written

$$\text{power } p = \lambda\, \tfrac{1}{2}\rho V^3 A$$

where A = test section flow area and λ is a coefficient which varies primarily with the tunnel design and the flow Mach number.

For a given tunnel, Mach number and pressure, this simplifies to

$$p \propto \sqrt{T}$$

showing that fan power reduces as Reynolds number is increased by means of reduced temperature.

2.2 Cooling

There are two basic methods open for exploitation. One is the near-isentropic expansion of a gas from high pressure storage to the test stagnation pressure. The gas may be fairly cool in storage but is further cooled in the expansion process, and then used in the tunnel. The expansion pressure ratios required in isentropic processes are easy to calculate. With a diatomic gas beginning at room temperature a pressure ratio of 40 is required to expand to 100K. Several projects fall into this category and will be discussed in Paper 16.

The alternate is to inject a cryogenic liquid (perhaps produced in plant separate from the tunnel, but stored alongside) into the test gas, using the latent heat of the coolant and in some circumstances an appreciable component of sensible heat. It is common to use liquid nitrogen although combinations of nitrogen and oxygen could be used, at the cost of some complication, if there was a strong need to retain an air mixture. The quantity of liquid nitrogen needed as a coolant may be calculated with reasonable precision from the approximate expression

$$\text{cooling effect of } LN_2 \simeq 100 + 1.2\, T_0 \text{ kJ/kg}$$

where T_0 is the tunnel stagnation temperature. A more precise expression is available[11].

This is dissipated in several ways. There is a requirement to absorb fan power or, in the case of the induced flow tunnel, to cool the inducing air. For tunnels operating at 100K, in the former case the exchange rate, LN_2 flow rate to fan power, is 0.0045 kg/sec per kW., and in the case of the induced flow tunnel supplied with air at 300K the ratio of LN_2 flow rate to inducing air flow rate is about 0.9. There is also the need to account for the cooling of at least a proportion of the tunnel structure, the proportion depending on the thermal insulation scheme and on run time. However the exchange rate, expressed as the ratio of LN_2 mass to structure mass, in cooling from 300K to 100K is about 0.25.

Additional coolant is required to absorb heat inflow through insulation. The quantity required is strongly design- and run-time dependent and it is difficult to provide very general information. However the specific example of the Langley 0.3 Meter Transonic Cryogenic Tunnel(12) may be cited for guidance. In this recent reference the proportion of LN_2 consumption estimated as attributable to heat inflow is $1\frac{1}{2}\%$ of the total. While the authors naturally are guarded about the general applicability of the information, as I must be, it is nevertheless a useful guide to expectations for fan driven transonic tunnels. One estimate for low speed tunnels(13) attributes up to 10% of the LN_2 consumption to heat leakage.

While the total requirements of a cryogenic wind tunnel for coolant and therefore cooling power depend on its design and operating cycle, studies have shown that the total energy consumption of a cryogenic wind tunnel is appreciably less than a conventional tunnel when comparisons are made on the basis of equal pressure, Mach and Reynolds numbers.

2.3 Controlled Variables

The cryogenic wind tunnel has, in contrast to a conventional tunnel working at essentially constant temperature, the new controllable variable of temperature which can be exploited in a way which is not always immediately apparent. The last comment is made with confidence because those of us who were involved in the earliest days did not see the point for a while.

The cryogenic pressure tunnel has the three independently controllable test variables of speed, pressure and temperature. These may be used in various combinations to control the Mach and Reynolds numbers of the test. In principle only two of the variables are needed and therefore the third is free to be used to control some other feature of the test conditions. The potential usefulness of this freedom is in controlling the loads on a model and its consequent aeroelastic deformation, because in some testing the variations of data due, say, to Reynolds number effects can be clouded by the aerodynamic consequences of the deformation. It is usual therefore to regard the three variable test conditions as controlling the Mach number, the Reynolds number and the dynamic pressure. Through the independent control of dynamic pressure there is independent control of model shape (at least to a first order) which is a unique feature of the cryogenic wind tunnel and is particularly important in transonic tests where stresses and deflections can be large.

2.4 Energy Recovery

Despite the quite enormous savings in capital costs and significant reductions in energy consumption offered by the cryogenic wind tunnel in relation to competing continuously-running designs, viewers of the cryogenic wind tunnels now in operation quite often look at the exhaust plume and ruminate on the possibilities of recovering in some way the "cold" and the energy so represented. The notion is as old as the cryogenic wind tunnel and it is quite proper for it to be kept in mind. There is much scope for inventiveness and there are many possible recovery schemes.

An essential feature must be practicality in the light of the duty cycle of the tunnel. Typically the tunnel is used only intermittently, rather unpredictably and then with strongly varying conditions. The user will not want to have a test compromised significantly by the recovery scheme. These considerations eliminate some possibilities. In particular I think those which aim to recover cold gas or liquid from a pressurised tunnel for recycling, either of which are possible in principle, are impractical for application to wind tunnels.

However, to illustrate the possibilities, the following is an outline of one scheme which might offer useful energy savings while having the necessary responsiveness. The notion, applicable perhaps to the fan driven pressurised tunnel, is merely to expand the exhausting nitrogen gas through a turbine. Calculations using idealised thermodynamics and neglecting flow losses are summarised on Figure 2, where the power output available from the turbine is shown in relation to the tunnel's fan power as a function of tunnel temperture and pressure. The LN_2 flow rate into the tunnel is assumed just that required to absorb fan power. The recovery expressed in this way is independent of test Mach number. There are two sets of curves, the lower full curves assuming the exhausting gas to be expanded directly from the tunnel, the other broken curves assuming the gas to be first heated to ambient temperature in a heat exchanger before expansion. It can be seen that quite a large proportion of the motor power is recoverable under some conditions, perhaps 30% with the gas warmed to room temperature at high pressure. While the maximum proportion of recoverable power

rises as tunnel temperature falls, in fact the absolute value of turbine power for a particular tunnel, pressure and Mach number is roughly constant. Idealised calculations usually are expected to overestimate, but in this case there is the additional factor of LN_2 flow for heat leakage and for cooldown which would raise flows and perhaps leave the power forecasts on Figure 2 not too far from realistic.

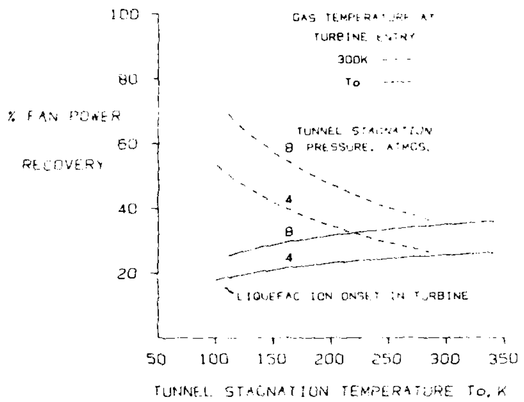

Figure 2: Energy recovery by expansion of tunnel exhaust gas in a turbine, relative to tunnel drive power. Ideal expansion from a fan driven tunnel.

There are of course many practicalities to be considered alongside thermodynamic cycles, in this scheme these include the control of flows and turbines, and the effects of re-liquefaction near the outlet of the turbine. The costs and complexities of the additional hardware must be weighed against any reduction in the direct running cost and motor and land-line capital costs. These comments will apply to any such energy recovery scheme.

3. NOTES ON A CRYOGENIC LOW SPEED AND A CRYOGENIC TRANSONIC WIND TUNNEL

3.1 As an introduction to cryogenic wind tunnel design and operation, subjects which will be expanded upon in later lectures, I am using the example of the 0.1m cryogenic wind tunnel at Southampton University[14]. This was built originally for an investigation into the possibilities for surface flow visualisation at low temperature. It ran in 1977 and was used successfully for that task[15]. Since then it has been further developed (with material help from NASA under Grant NSG-7172) and used in a series of Undergraduate final year projects (titles appear in the Appendix), the most recent aimed at bringing the tunnel to the point where it is suitable for the teaching of fundamental aerodynamics, in particular the demonstration of Reynolds number effects.

I believe the existence of this size of tunnel represents a *double need*, a need for economical instruction in cryogenic testing, and for the economical development of instrumentation and other devices for use in other larger tunnels.

The tunnel is closed circuit, unpressurised, fan-driven and cooled by liquid nitrogen sprayed into the circuit just downstream of the test section. At low temperature the test gas is therefore nitrogen; at room temperature and above it is usually air. There is a chimney to carry exhaust gas out of its building. The test section is 4 inches (102mm) square, and the overall dimensions are 7½ feet (2¼m) long by 3½ feet (1.1m) high, with the circuit centreline in the vertical plane. The drive motor of 4kW has a variable frequency power supply driving the fan at up to 7,200 r.p.m. The principal materials of construction are aluminium and fibreglass.

Aside from the obvious differences between a cryogenic tunnel and one of similar design for use at normal temperature, such as the need for circuit insulation and a sensible choice of materials, the only significant difference in this tunnel lies in the design of a bearing housing. The bearing is inside the circuit and supports the fan. The housing, sketched on Figure 3, is thermally insulated and heated with two 250W cartridge heaters, the temperature being controlled at a 50 deg. C set point by a thermocouple-activated relay. The tunnel has other heaters in its circuit to warm it more quickly following a cryogenic run and incidentally allowing the tunnel to run at elevated temperature.

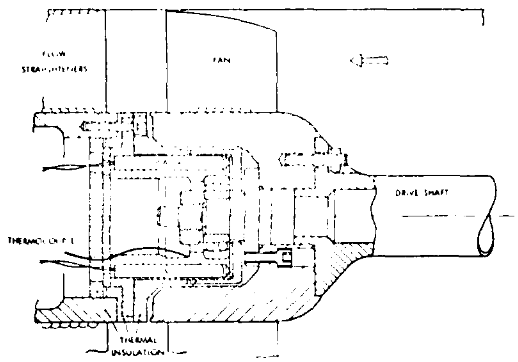

Figure 3: 0.1m low speed cryogenic wind tunnel at the University of Southampton. Fan and heated bearing.

The available variations of fan speed and gas temperature provide test Mach numbers up to 0.4 and unit Reynolds numbers up to 50 millions per metre. Of value in teaching is the wide range of Reynolds number, the ratio of the maximum to the minimum usable values being close to 100:1. The operating envelope, which is in most respects typical of a low speed atmospheric pressure cryogenic tunnel, is shown on Figure 4.

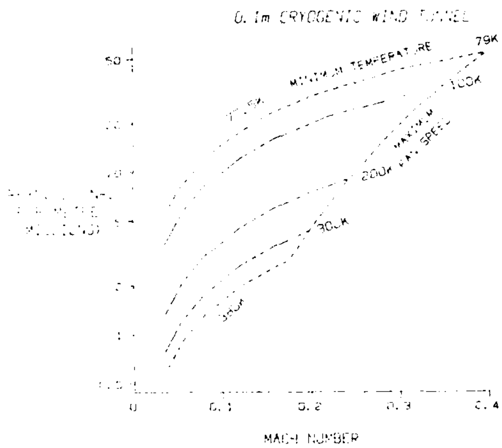

Figure 4: Operating envelope.

Test conditions can be manoeuvred to any point inside the envelope, to the high temperature boundary by use of the circuit heaters. The tunnel has a microcomputer-based control and data logging system. The computer is a Commodore PET with a multi-function interface (A-D, D-A and relay switching), acquiring temperature, pressure and other data, and providing closed-loop control of the tunnel and the experiment through relays and D-A. The cycle time of the controller is approximately 4 seconds. A block diagram of the complete system is shown on Figure 5, together with an outline of the tunnel circuit.

The operator can select one of a variety of control modes. For example he can select a Mach number hold (say while temperature is being changed: in this case a decrease in temperature is accompanied by a decrease in fan speed in proportion to the decrease in the speed of sound) or select constant Reynolds number or constant temperture, all within the confines of the envelope of Figure 4. Temperature may be controlled manually, or automatically by switching the circuit heaters. An example of the locus of a typical one hour run is on Figures 6. Figure 6(a) shows temperature and fan speed, the controlled variables, changing through the run in apparent disorder. However for much of the run time they were in fact varying in response to the operator's demands (which were changed from time to time) for certain constant values of Mach or Reynolds numbers, or for constant temperture.

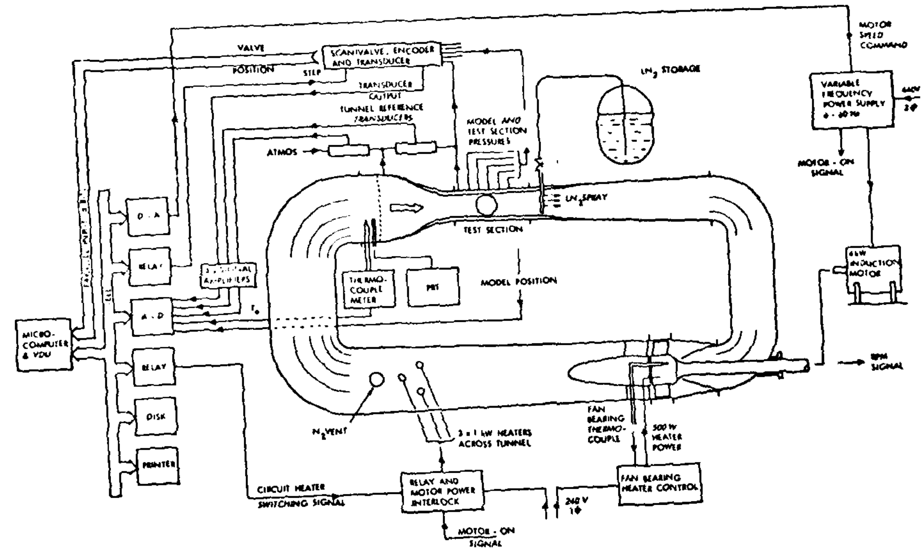

Figure 5: Cryogenic wind tunnel systems block diagram.

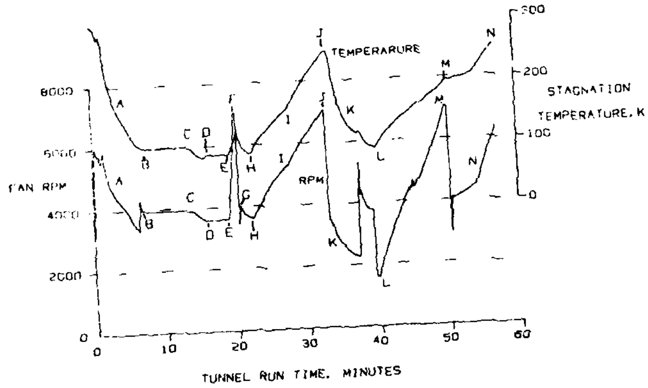

Figure 6(a): The variations of fan speed and stagnation temperature during a typical one-hour run, in response to the pattern of demands from the operator, illustrated in Figure 6(b), for changes in Mach and Reynolds numbers.

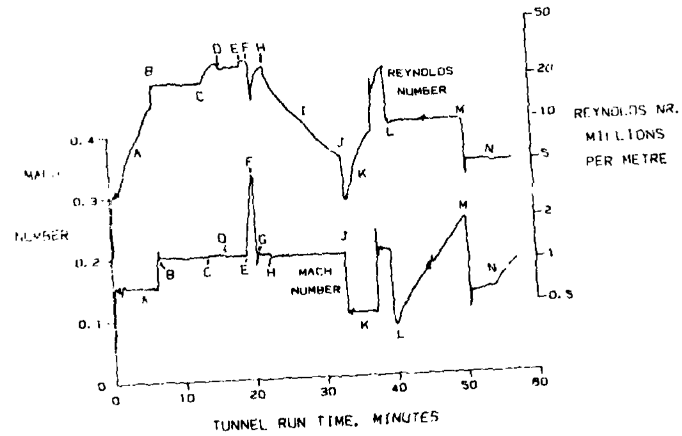

Figure 6(b): Mach and Reynolds numbers selected by tunnel operator.

Features of the traces on Figure 6(a) are labelled. These may be related to the labels on Figure 6(b) which shows the corresponding variations of Mach and Reynolds numbers. The traces (plotted from the run data file, complete sets of data having been sampled about every 4 seconds) have been analysed statistically in selected areas. Table 1 summarises events and, where a parameter is being held constant, shows the standard deviation of that parameter through the period.

Table 1: An outline of events during the one-hour run illustrated on Figure 6, with the standard deviations of controlled parameters

Activity	Period			Value of controlled parameter			Standard deviations		
	Label	Seconds	**	Mach no.	Reynolds no.*	Temperature K	Mach no.	Reynolds no.*	Temperature K
7 minute cooldown, 299K-99K at constant Mach no.	A	366	82	.15	-	-	0.0024•	-	-
Steady tunnel conditions	B-C	401	89	.2	20.4	99	0.0005	0.115	0.274
Period of constant demanded Mach no.	B-E	724	156	.2	-	-	0.0009	-	-
Steady tunnel conditions	D-E	185	54	.2	25.9	85	0.0007	0.372	0.707
Warmup, LN_2 off, 85K to 111K at constant Reynolds no.	E-F	59	14	-	28.5	-	-	0.127	-
Cooldown to 85K at constant Mach no.	G-H	97	22	.2	-	-	0.0009	-	-
Warmup, LN_2 off, 85K to 245K, constant Mach no. (circuit heaters on at 1)	H-J	639	141	.2	-	-	0.0008	-	-
Constant demanded Mach no. during temperature changes	G-J	736	162	.2	-	-	0.0017	-	-
4 minute cooldown, 247K-113K at constant Mach no.	K	246	54	.1	-	-	0.0013	-	-
Warmup, LN_2 off, 89K-190K at constant Reynolds no.	L-M	619	140	-	9.9	-	-	0.171	-
Warmup, LN_2 off, 195K-250K at constant Reynolds no.	N	359	81	-	5.0	-	-	0.023	-

** Number of samples analysed
* Millions per metre
• 0.0009 from 2 minutes into cooldown

This evidence shows that indicated Mach number can be held constant for useful periods of up to 10 minutes or more (long enough for the requirements of most aerodynamic tests at one tunnel condition) to a standard deviation of better than 0.001, rising only to about 0.002 during relatively rapid temperature changes. When Reynolds number was being controlled the standard deviation was 0.5% to 2% of the absolute value, which may be good enough. The limited information given in Table 1 on the constancy of temperature when under automatic control indicates a standard deviation of about 0.5 degrees. This is confirmed by other test data from 80K to 380K, which also shows that when temperature is manually controlled the standard deviation is worse, at 1 to 1.5K.

This example of a fairly typical run is intended to show several features:

1) the rapidity with which test conditions can be changed. This is not a feature of the control system in the case of this tunnel,

2) the versatility of digital control in allowing control over several selected test parameters. It should be mentioned also that automatic control is useful in easing considerbly the workload of the operator,

3) the quality of control, which is seen to be good despite the fact that no attempt has been made to optimise the control algorithms.

There is one procedure which is carried out with ease under automatic control but which is probably quite difficult to do manually (although it has not been attempted manually on this wind tunnel). That is the holding of constant Reynolds number by continuously adjusting the fan speed while temperature is ramped slowly up or down. This is the way in which variations of test Mach number are introduced at constant Reynolds number. The example is presented because as yet there are so few fan-driven cryogenic tunnels in service for which analyses of such information is available.

A final point on temperature and its control. It is fairly natural that this should be an emotive subject in relation to the cryogenic wind tunnel. However it should be noted that the precision with which the long-term (and possibly the short-term) variations of stream temperature are now being controlled is much better in the case of the cryogenic wind tunnel than is possible in most conventional transonic or subsonic wind tunnels. This is probably as it should be, and the precision which was demanded is just another consequence of the cryogenic wind tunnel being born into an age when new standards are being set.

3.2 The 0.3m Transonic Cryogenic Tunnel at NASA Langley Research Center

This wind tunnel is singled out for special mention because of the outstanding record of the tunnel and those people associated with it, in promoting the acceptance of the concept of cryogenic testing.

First some historical facts. the tunnel was designed, built and run inside a year with the vigour characteristic of the US nation, with a main objective of proving the concept by demonstrating at transonic speeds what we now accept, and which with the benefit of hindsight even seems odd to question, that Reynolds number obtained by temperature is the same as Reynolds number obtained by other means. The evidence was quick to arrive, leading also in a short time to the decision by the U.S. to adopt the concept for their large high Reynolds number transonic tunnel which is now running and known as NTF. Since its proof-of-concept days 0.3m has been fitted with a two-dimensional test section and for years has been used for routine testing at chord Reynolds numbers up to 70 millions. The tunnel is run two shifts a day and at the time of writing is still the only cryogenic wind tunnel which has been used on a routine basis for production aerodynamics. The total running time is now in excess of 5000 hours, a large proportion of which has been at cryogenic temperatures. During this time it has pioneered the art and science of testing, of control, instrumentation, model making, safety and construction of the fan-driven transonic pressure tunnel. 0.3m has done more than any other tunnel to convince the world of the merits of the cryogenic concept, while at the same time providing a mass of aerodynamic and operational data. This achievement is in my opinion a fine tribute to the engineers who evolved the concept, to the administrators who backed the venture, to the designers and to the engineers who have since come along and carried out the day-to-day operating, maintenance and updating of the tunnel.

Now to close, a cautionary note. The aim of the cryogenic wind tunnel is to make a step forwards in the quality of aerodynamic testing by bridging the Reynolds number gap. In doing so we must be sure that we do not introduce inadvertently some feature which tends to degrade the potential for improvement in quality. We are here to learn, from experts in the field, of the measures being taken around the world to introduce the tunnel into more general use following the lead of 0.3m, measures ensuring the proper contribution of the cryogenic wind tunnel to a general trend towards excellence in the discipline of experimental aerodynamics.

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APPENDIX

UNDERGRADUATE PROJECTS WITH THE 0.1M CRYOGENIC WIND TUNNEL AT THE UNIVERSITY OF SOUTHAMPTON

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BASIC CRYOGENICS AND MATERIALS.

by
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SUMMARY

This paper summarises the effects of cryogenic temperatures on the mechanical and physical properties of materials. Heat capacity and thermal conductivity are considered in the context of conservation of liquid nitrogen, thermal stability of the gas stream and the response time for changes in operating temperature. Particular attention is given to the effects of differential expansion and failure due to thermal fatigue. Factors affecting safety are discussed, including hazards created due to the inadvertent production of liquid oxygen and the physiological effects of exposure to liquid and gaseous nitrogen, such as cold burns and asphyxiation. The preference for using f.c.c metals at low temperatures is explained in terms of their superior toughness and the limitations on the use of ferritic steels is also considered. Non-metallic materials are discussed, mainly in the context of their LOX compatibility and their use the the form of foams and fibres as insulants, seals and fibre-reinforced composites.

1. INTRODUCTION

The industrial production and handling of cryogenic fluids such as liquid nitrogen, oxygen, hydrogen and helium, as well as liquefied natural and petroleum gasses is now based on mature technologies developed and refined over many decades. The needs of a cryogenic wind tunnel using large quantities of liquid nitrogen do not differ significantly from those of, for example, a large chemical plant or food freezing factory and thus much of this technology is directly transferable. It is, however, important to recognise that the majority of those involved in running or using a cryogenic wind tunnel are unlikely to have had previous experience of cryogenic fluids. It is therefore particularly important to ensure that the accumulated experience on the safe handling of cryogenic fluids is also passed on to these new users. Much of this experience has now been gathered together in manuals and texts such as references 1, 2 & 3. This information should be digested and understood not only by those with managerial responsibility for safety, but also by those directly involved, and as far as is practical, by those indirectly involved in the use of cryogenic fluids. Unjustified alarm created in the minds of those in receipt of a suitable training program can usually be allayed by a full and frank examination of the facts. Justifiable alarm is better exposed before an accident, when remedial action can be taken, than after a tragedy. Finally, the old adage "familiarity breeds contempt" is unfortunately true and even experienced personnel can get careless. Cryogenic fluids such as liquid nitrogen deserve a healthy respect, but when handled with care, their use can open up new areas of technology such as the cryogenic wind tunnel. In view of the importance of using the correct procedures in the design, construction and operation of cryogenic tunnels, those sections of this paper that have a direct bearing on safety will be highlighted by the use of bold print.

Those involved in the design and construction of cryogenic wind tunnels and the models that are to be tested in them need a more thorough understanding of the properties of cryogenic fluids and materials and techniques of construction. In the previous AGARD lecture series No. 111 on Cryogenic Wind Tunnels, (Ref. 4), the author gave two lectures on the Physical and Mechanical Properties of Materials and Dr. R. G. Scurlock gave three lectures on Cryogenic Engineering. These lectures set out basic principles for the safe handling of cryogenic liquids and the construction of cryogenic equipment and, five years later, these principles are equally valid. In this lecture we will try and distill the essence from the material contained in these five lectures and update it in the light of the progress made since the first lecture course. For a more thorough understanding of the subject the reader is, however, encouraged to consult the original papers, particularly as much numerical data on the physical and mechanical properties of materials was collated in the tables therein (Refs. 5 & 6). Further valuable information is also contained in Toblers excellent report on "Materials for Cryogenic Wind Tunnel Testing" (Ref. 7)

Before considering these factors in detail, it is worth taking a brief overview of a typical large installation. Firstly, let us consider the storage and transfer of the large quantities of liquid nitrogen needed to run a tunnel. In principle, this is virtually identical to the situation which exists in, for example, a large food freezing plant. The storage vessels, pumps, valves and control equipment, all serve the same purposes and there are, therefore, sound reasons for considering them as a commercial package once the relevant design specification has been established. Thus, for example, it should not matter whether 9% nickel steel, 304 stainless or 5083 aluminium is chosen for the construction of the LIN storage vessel as long as it is carried out by a technically competent organisation. In many respects the design and construction of the transfer line should also be a relatively simple commercial consideration once local constraints and requirements have been identified.

Secondly, in the design and construction of the tunnel itself it is necessary to bear in mind the extra constraints that cryogenic operation will introduce. For example:

- thin, light structures cool down more rapidly and evaporate less cryogenic fluid than do heavy sections, thus, if fast thermal response is required it is essential to minimise the thermal mass of the structure.

- **insulation is necessary to cut down the heat inleak to the working space and hence the effective refrigeration power used. This insulation can be applied either internally or externally and the implications of this decision are manifested in considerations of the smooth profile of the inner liner in the first case and in the toughness of the pressure shell at cryogenic temperatures in the second.**

- all materials contract to a greater or lesser extent when they are cooled and one of the essential aspects of the successful design of cryogenic equipment lies in avoiding the problems created by differential contraction caused by temperature gradients or the juxtaposition of dissimilar materials.

- some materials embrittle at low temperatures and it is of critical importance to select materials with strengths and toughnesses adequate for their intended duty. The failure of even a non-structural component could possibly cause damage further down the tunnel, or lead to the premature end of a test run.

- all materials used must be compatible with their working environment both internally and externally. Design must ensure the prevention of accidental condensation of liquid oxygen, particularly in the presence of hydrocarbon based polymers which are LOX incompatible.

Thirdly, it is important that designers and operators are aware of the differences that a low temperature environment will induce in a tunnel and its associated equipment as compared to conventional operation at ambient temperatures. Thus, certain aspects of the model suspension and force measuring systems will have to be reconsidered in the light of their cryogenic operating environment. For example:

- the materials used to construct the sting assembly have to be very strong and stiff. In many alloys high strengths are associated with low toughnesses and as the strengths of all metals increase at low temperatures, it is essential to ensure that their toughness does not fall to unacceptably low levels: current state of the art technology seems to favour the various grades of maraging steel and the precipitation hardened and high-nitrogen forms of stainless steel for sting construction.

- if the force balance systems are to operate at ambient temperature in a cryogenic tunnel, heaters must be used to warm the appropriate regions. Low conductivity materials have to be used to provide the necessary heat breaks between warm and cold regions, while high conductivity inserts can even out unwanted temperature gradients.

- alternatively, if the whole system is to operate at low temperature it has to be possible to calibrate out the variations in the gauge constants brought about by changes in the electrical resistivity of the metallic films or wires and adequate moisture proofing is essential.

- provision should be made for the removal of the model assembly from the test section without the need to warm up the whole tunnel. Furthermore, a cold model assembly should be allowed to warm up in an atmosphere of dry nitrogen if problems caused by moisture condensation and frost build up are to be avoided.

At this stage it is worth emphasising that care needs to be exercised in the use of data taken from compilations and reference manuals because some properties are more "structure sensitive" than others. For example, the electrical and thermal conductivities, strength, ductility and toughness of materials are properties that are highly dependent on the microstructural and chemical condition of the material. In contrast, the specific heat, thermal expansion and elastic moduli are relatively unaffected by the presence of structural defects. Thus, although it is possible to apply the data taken from the literature for the structure-insensitive group of properties, it would be unwise, and even dangerous, to use uncritically the values given for the defect sensitive properties. These should be used for guidance only and if at all possible, they should be backed up by data obtained experimentally on material obtained from the suppliers of the batch of material to be used: in the absence of such experimental verification, generous safety margins should be applied to the literature data.

2. THERMAL AND OTHER PHYSICAL PROPERTIES OF MATERIALS

2.1 Heat Capacity and Specific Heat

Information on the heat capacity or specific heat of materials used in the construction of cryogenic equipment is necessary in order to calculate the energy that has to be supplied for cool-down to the operating temperature. Structures with the highest heat capacities require the largest amount of cooling and this has to be supplied by the latent heat of the evaporating liquid or by the sensible heat of the cold gas. For structures which have to undergo frequent cooling and warming cycles, it is important to minimise the total heat capacity, or thermal mass, to achieve both low liquid boil-off rates during cool-down and also short cooling times: for equipment that rarely warms up once it is cooled, low heat capacities are not so important. A further, and highly relevant, example of the effect of thermal mass may be illustrated by comparing the operating experience of the NASA 0.3-m TCT with that of the tunnel at the University of Tsukuba, Japan. In the NASA tunnel virtually no problems were experienced in controlling the temperature of the working gas by varying the liquid nitrogen injection rate, while the Japanese group found the maintenance of steady temperatures much more difficult. The clue to this difference is to be found in the designs of the tunnel liner and insulation system. The NASA tunnel is insulated on the outside of the 6061-T6 aluminium alloy pressure shell and thus a large thermal mass of metal is cooled down to the working temperature. The thermal inertia of this large mass evens out fluctuations in the gas temperature that would otherwise be created by variations in the liquid nitrogen injection rate. In the Tsukuba tunnel the insulation is inside the mild steel pressure shell and the inner wall is thin and has a low thermal mass. It is thus unable to absorb much heat without its temperature rising and the liquid nitrogen injection control system has to work much harder to achieve temperature stability. On the other hand, deliberate changes in the operating temperature are achieved more rapidly in the Japanese tunnel.

For heat balance calculations it is, in fact, the enthalpy, $H = \int C_p\, dT$, which is of most direct use and in Reference 9 tabulated values of the enthalpy relative to absolute zero are given together with the specific heat at constant pressure, C_p, for a range of metals and non-metals. The specific heats of all materials drop off at low temperatures eventually to become zero at 0 K, and the very low values found at hydrogen and helium temperatures can cause large temperature differences to be set up by a small heat-influx. At liquid nitrogen temperatures and above these effects are not so severe.

Although large amounts of cold work may cause a slight decrease in heat capacity, for practical purposes specific heats are largely unaffected by the normal range of conditions found in metals. The

specific heats of pure crystalline solids over the complete temperate range is given by the Debye theory and knowledge of the characteristic temperature, θ_D, allows calculation of the specific heat at the required temperature.(Ref. [illegible]). Specific heats of alloys at room temperature are given approximately by the Kopp-Newman rule of mixtures in which the specific heat of a metallic solution is given by the sum of the products of specific heat and molar fraction for each constituent element. Although the rule gets less applicable at low temperatures, in the absence of alternative data it gives an acceptable first approximation. Furthermore, it is worth noting that the lattice structure has a strong influence on specific heats as illustrated by the observation that the measured specific heat of f.c.c. austenitic stainless steels are closer to those calculated for gamma iron than those measured on the b.c.c. alpha iron. The specific heats of non-crystalline and amorphous materials cannot be described by the Debye theory and there is, therefore, no satisfactory alternative to measured values for materials such as glass and amorphous ceramics, as well as all polymers, elastomers, composites and adhesives. When considered on a unit mass basis most of these materials have high heat capacities compared to metals, but this discrepancy is reduced if they are considered on a unit volume basis.

2.2 Thermal Conductivity

Conduction of heat in solids takes place through the vibration of their lattice atoms, and in the case of metals, by the movement of their conduction electrons. Any mechanism which makes these processes more difficult lowers the thermal conductivity of the material and hence high conductivities are found in pure, strain free, large grain or single crystal metals and non-metals, while low conductivities are associated with impure, stressed, amorphous or microcrystalline structures. As it is difficult, if not impossible, to recognise these different conditions by looking at the surface of a material, and as the physical and mechanical history of the sample is rarely well documented, great uncertainties can arise in using thermal conductivity data from the literature. However, in many cases, conductivities at one extreme or the other are required - for example, very low conductivities where heat breaks are required to reduce heat influx, or very high conductivities to minimise thermal gradients. In general, good conductors are materials of high purity and in an annealed state, while bad conductors are either alloys with many components and complex microstructures, or non-metals with amorphous or microcrystalline structures. Still lower conductivities may be obtained by increasing the number of interfaces crossed by the heat flux. For example, stacks of stainless steel discs may be used for compressively loaded, thermally-insulating supports, while the combination of many fine glass filaments with a thermo-setting plastic matrix (G.R.P) gives a material with the highest known ratio of tensile or compressive strength to thermal conductivity. The use of G.R.P. supports to separate the inner and outer skins of modern vessels for storing cryogenic liquids is, in a large measure, responsible for the low boil-off rates currently achieved.

It should, however, be noted that although the amorphous or microcrystalline structures of most non-metals make them very efficient thermal insulators, it also makes them very brittle, especially in the bulk form and they can be excessively prone to thermal shock if cooled rapidly. Furthermore, variations in their density, structure and processing history can change their thermal conductivities by about an order of magnitude as well as causing considerable anisotropy, so care has to be taken in extracting suitable values from the literature.

2.3 Thermal Expansion

This is probably the most important of the physical properties because the stresses set up in components by differential thermal expansion can very easily cause severe distortion or, at the worst, failure. The total linear contraction of a number of representative materials is shown as a function of temperature in Fig. 1. It can be seen from the figure that the total linear contraction at 77 K varies from about 0.05% for Invar and Pyrex glass to over 2% for some thermosetting resins, and it is not surprising, therefore, that problems can arise when materials are used together without adequate forethought. Problems can, in practice, usually be resolved into two basic categories.

i) those in which only one type of material is involved and where differential contraction is a result of temperature gradients.

ii) those in which the same temperature gradient is applied across two or more materials of different expansion coefficient.

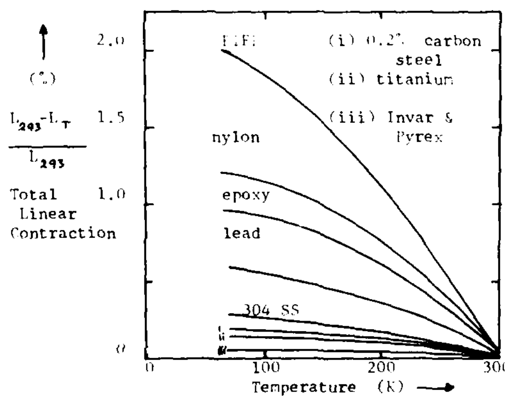


Figure 1. Total Linear Contraction of Selected Materials

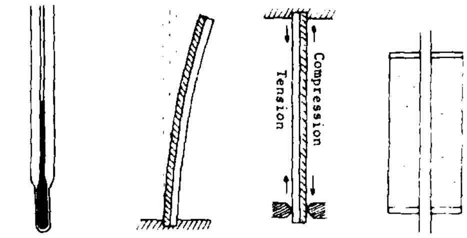
Considering first the case of dissimilar materials, a common mercury in glass thermometer uses the large differences in expansion coefficients between the two components, but no stresses are set up as the mercury is free to move inside the glass tube (Fig. 2a). In contrast, a bi-metallic strip consists of two metals firmly fixed together, and when the temperature decreases the free end moves towards the side containing the metal with the higher expansion coefficient (Fig. 2b). If the end were not free to move the metal with the higher expansion coefficient would be put into tension and the other metal into compression (Fig. 2c). An idea of the forces that can be set up by contraction in dissimilar metals can be obtained by considering the hypothetical arrangement illustrated in Fig. 2(d), in which co-axial copper and steel pipes joined at both ends are cooled to 80 K. The total linear contraction of copper is 302 $\times 10^{-5}$, while that of a 0.2% carbon steel is 192 $\times 10^{-5}$, a difference of 110 $\times 10^{-5}$ or just over 0.1%. Thus the differential strain is slightly larger than that considered to give the 0.1% proof stress, which in copper at 80 K is about 88 MPa. If the joint between the two metals were a soft lead-tin solder it would have to yield and flow in order to accommodate this degree of mismatch. (Data from Ref. 10)

An even more relevant example is illustrated in Fig. 2(e) which shows a section of an externally-insulated, closed-circuit cryogenic tunnel. When cold the wall of the tunnel contracts relative to its warm mountings and, as one end is effectively clamped by the fan shaft bearing, the other end must be able to move to prevent thermally-induced stressing on cooldown. In the NASA LaRC 0.3-m TCT this is accomplished by supporting the wall on a stainless steel supports which slide on re-inforced PTFE pads. Differential contraction between the inner and outer walls is a common design problem in transfer lines for cryogenic fluids and some form of expansion joint has to be built into the system. It was noted earlier that the total linear contraction of Invar from 300 to 77 K was very much smaller than other alloys, about 1/6th of that of austenitic stainless steels and 1/8th of that of aluminium alloys. Thus a transfer line with the inner wall made from Invar would need only 1/6th or 1/8th as many expansion joints as it would if made from stainless steel or aluminium alloy respectively and the savings thus achieved are sometimes more than enough to offset the higher material and fabrication costs associated with Invar.

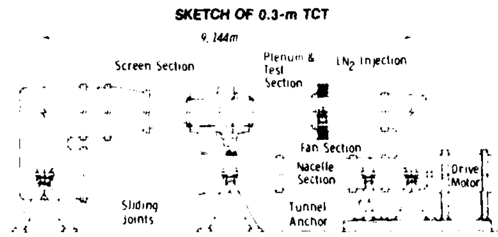
A further example of mismatched materials is illustrated in Fig. 2(f) by a flanged joint between aluminium alloy and stainless steel pipes. Aluminium alloys contract more than stainless steels and if an aluminium alloy bolt were used its loading would be increased as it contracted more rapidly than the stainless steel flange. It is possible that the bolt might in fact fail on cooling: if not it would yield and stretch so that on warming to room temperature it would now be too long to compress the gasket adequately and a room temperature leak would be created. The use of a stainless steel bolt would also cause problems because on cooling it would contract less rapidly than the aluminium flange and so be unable to keep the same compressive stress on the gasket - the likely outcome being a low temperature leak which would then seal itself up when the joint were rewarmed to ambient temperature. This type of low temperature leak will be recognised by those with cryogenic experience as a source of considerable frustration!

One elegant solution to this problem is shown in Fig. 2(g). A long stainless steel bolt passes through the centre of a Monel compensating sleeve as well as through the two flanges, the length of the Monel sleeve being calculated to compensate exactly for the lower contraction in the bolt. The total linear contractions at 80 K relative to 293K are 391 $\times 10^{-5}$ for aluminium, 236 for Monel and 285 for type 304 stainless respectively, hence the difference between the stainless bolt and the aluminium flange is 106 $\times 10^{-5}$ and that between stainless and Monel is 49 $\times 10^{-5}$. If the aluminium flange were 10 mm thick a Monel sleeve 10 $\times$106/49, i.e. 21.6 mm long would be needed for exact compensation. The same principle may be used for joints between 9% nickel steel and aluminium flanges by using an Invar (Nilo 36) sleeve to compensate for the contraction in the 9% Ni steel bolt.

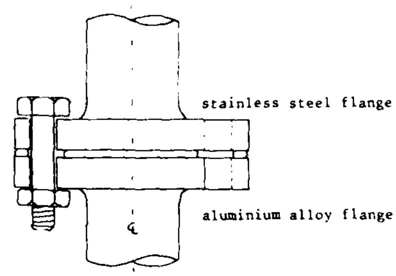
Returning to the case where temperature differences can cause problems even when the material is the same, Fig. 2(h) shows schematically a situation in which co-axial, thermally-insulated vessels are joined at their extremities. If the vessels were made of mild steel the total linear contraction of the inner shell at 80 K would have been 192 $\times 10^{-5}$ relative to the outer shell which remained at ambient temperature.



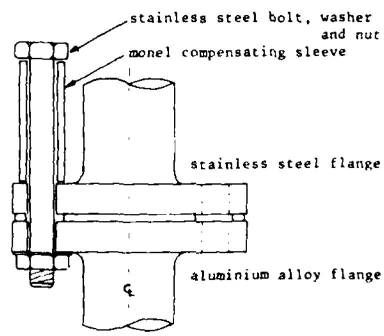
2(a) 2(b) 2(c) 2(d)



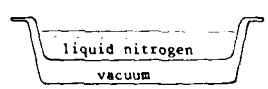
2(e)



2(f)



2(g)



2(h)

Figures 2(a) to (h) Examples of Differential Thermal Contraction caused by Dissimilar Materials or Temperature Gradients.

This strain was too large to be accommodated by the mild steel which was not only below its ductile-brittle transition, but in all probability embrittled by the welding used in its fabrication.

The whole question of fits and clearances at low temperatures has to be kept very much in mind. Most of us are familiar with the practice of heating a gear wheel before placing it onto a shaft so that it will shrink to a tight fit on cooling. Some will also be aware that the same operation is sometimes carried out by cooling the shaft with liquid nitrogen prior to fitting the gear so that the required fit is obtained when the shaft expands on rewarming to room temperature. These examples should be remembered when constructing models, balances or other fittings where there are close fits and small clearances. On cooling these clearances could either decrease and cause a seizure, or increase and lead to looseness and possible loss [illegible]. This can also manifest itself in changes in the clamping force applied to models which could decrease on cooling and allow the model to vibrate loose, or increase and possibly cause damage. Reference to [illegible] will remind us that these problems are likely to be particularly severe where non-metallic materials are involved as their total linear contractions are so large.

Finally, it is worth reiterating the comment made earlier about thermal shock. We have now seen that most non-metals have low thermal conductivities and high expansion coefficients, and we will find later that many of them also become embrittled at low temperatures. We thus have a combination of the three factors that lead to thermal shock and they are particularly severe if the materials are present in thick sections and/or cool down rates are high. Nevertheless, brittle materials can be used safely at low temperatures if enough care is taken. For example liquid hydrogen bubble chambers have plate glass windows for viewing ports which are cooled at a rate of a few degrees per day to prevent thermal shock. In the case of viewing ports for cryogenic wind tunnels, it is probably much better to follow the practice adopted in the [illegible] tunnel of [illegible] quadruple glazing purged with dry nitrogen. This not only [illegible] thermal shock but it cuts down the heat loss and prevents condensation on the outer skin. When [illegible] a multi layer system it is important to ensure that the purge gas is fed in from the warm side and exhausted at the cold face, as flow in the opposite direction is liable to cause condensation on the outer layers as they are cooled by the cold gas being fed from the inside.

3. PROPERTIES OF CRYOGENIC FLUIDS

The production of tonnage quantities of liquid oxygen and nitrogen by the fractional distillation of liquid air is a commercial process that has been developed continuously over almost 100 years. The availability of liquid nitrogen in tonnage quantities initially came as a bye-product of the requirement for large quantities of liquid oxygen for use in steel making, rocket fuels and other applications. Liquid nitrogen is readily available and relatively inexpensive and it was this combination that triggered the initial development of the prototype cryogenic wind tunnels in the early 1970's. Modern large tunnels such as the [illegible] consume so much nitrogen that a dedicated air separation plant is needed for their supply, the liquid oxygen now being the saleable bye product. Although the designer or operator of a cryogenic wind tunnel does not need to know the details of the commercial liquefaction process, some understanding of the basic thermodynamic mechanism of the separation of liquid air into its major constituents is desirable as incorrect design or operation of equipment that uses liquid nitrogen can cause the inadvertent production of liquid oxygen and create a potentially serious fire hazard. Basic aspects of Cryogenic Engineering are described in references [illegible] and [illegible].

3.1 Liquid Air, Oxygen and Nitrogen

The basic properties of liquid air and its constituents are set out in Table 1 and discussed in the next two sections.

Table 1 Properties of Liquid Nitrogen, Air, Argon and Oxygen (Refs. 1 and 11)

Property	Nitrogen	Air	Argon	Oxygen
Molecular Weight	28	28.9	40	32
Critical Pressure (atm.)	33.5	3[illegible].7	48.3	50.1
Critical Temperature (K)	126	132	151	154
Normal Boiling Point (K)	77.4	Bubble 78.8, Dew 81.8	87.3	90.2
Freezing Point (K)	63.2	-	84	54.8
Liquid Density at Normal Boiling Point (kg/m3)	808	876	1402	1138
Specific Gravity of Gas at 288 K and 1 atm.	0.97	1	1.38	1.10
Vol. Gas @ 288K & 1 atm. /unit vol. liquid @ B.P.	683	730	823	843
Latent Heat of Vaporisation (kJ/kg)	199	205	161	213
Specific Heat of Liquid Cp, (J/kg.K)	2.038	1.967	1.138	1.699
Liquid Viscosity (microPascal.sec)	158	163	256	188
Paramagnetism	none	oxygen / 5	none	strong
Colour	colourless	light blue	colourless	blue
Oxidizing Power	none	moderate	none	very strong

3.1.1 Binary phase diagram for oxygen-nitrogen mixtures

The binary phase diagram between pure oxygen, B.P. 90. K, and pure nitrogen, B.P. 77.3 K, is shown in Fig. 3. The composition of gaseous air is taken as 21% oxygen, 79% nitrogen, the minor constituents such as argon being ignored for the sake of simplicity. For air the dew point temperature, where droplets of liquid start to condense from the saturated vapour, is 81.8 K. The bubble point temperature, where bubbles of gas start to form in the saturated liquid, is 78.8 K. The horizontal tie-line drawn at 81.8 K connects the composition of the vapour, 21% oxygen-79% nitrogen, with that of the liquid with which it is in equilibrium, 50% oxygen-50% nitrogen, thus illustrating that the liquid is enriched with oxygen. In commercial air separation this enrichment is exploited by re-evaporating the liquefied air and allowing the nitrogen-enriched gas to rise up the column while the liquid descends and becomes progressively richer in oxygen as more and more nitrogen evaporates.

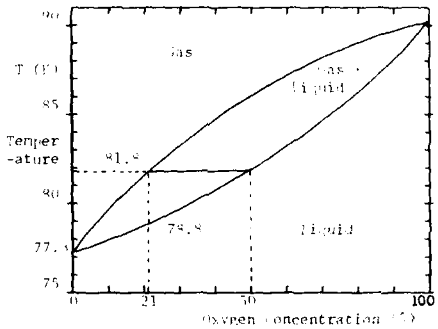


Figure 3. Nitrogen / Oxygen Phase Diagram

3.1.2 Inadvertent Liquid OXygen (LOX) formation.

It is, however, the inadvertent formation of oxygen-enriched liquid that is of much greater significance to the operator of a cryogenic wind tunnel. If air comes in contact with a surface cooled to temperatures below 81.8 K, it will condense and form a liquid enriched in oxygen. Subsequent evaporation of the nitrogen will further enrich the liquid until the remaining liquid is virtually pure oxygen. This can constitute an extremely serious fire hazard if there are combustible materials present. All hydrocarbon-based solids, liquids and gasses are LOX incompatible and the greatest care should be taken to avoid their presence in an oxygen-enriched atmosphere. If the cold surface is visible and covered with frost, its temperature is too high to condense liquid oxygen. If it looks wet and free of frost it is probably because the condensing liquid air has washed any frost away.

Despite its low temperature, liquid oxygen is an extremely efficient oxidizing agent and many materials, including some metals, will burn violently if ignited in its presence as the heat released during combustion is about an order of magnitude greater than the latent heat needed to vaporise the liquid to gas. Particularly reactive metals such as titanium and magnesium are a hazard even in the bulk form, while ferritic and austenitic steels, aluminium and zinc will burn fiercely when in the finely divided form of dust or fibres. All hydrocarbons, including ordinary clothing, human hair and tissue as well as many of the plastic foams and fibres used in insulation systems are LOX incompatible materials. Further details of the LOX compatibility of plastics materials are given in Table 10 of Ref. 5. There are two ways in which such materials may be used safely. The first is to apply an impervious vapour barrier to the outside of the insulation to prevent air ingress. This has the additional benefit of excluding water vapour which might otherwise lead to ice formation and degradation of the insulation material. The second is to ensure that the material is continuously purged with a dry, inert gas such as nitrogen. In practice these two techniques are best combined by gas purging the space inside the vapour barrier. A further point to note is that, although the appropriate measures may have originally been taken to prevent LOX condensation, subsequent servicing or modification may result in the incomplete re-establishment of an effective vapour barrier. In other cases, especially where the operatives have changed, potential hazards have arisen when LOX-incompatible materials have been substituted for the original, correctly-specified material. A further potential hazard can arise where control valves are hydraulically actuated if the inevitable fluid leakage from old installations is allowed to contaminate the insulation system or, as often happens, is allowed to saturate the flooring material. The combination of these saturated materials and oxygen-enriched air drifting down from an improperly insulated nitrogen-cooled surface would be a serious combustion hazard should they be inadvertently ignited. (Ref. 12).

3.2 Physiological Effects of Nitrogen and Other Safety Considerations

3.2.1 Cold Burns

Despite the apparent contradiction in terminology, the physiological effect of the exposure of human flesh to cryogenic temperatures is similar to that of a thermal burn. The affected tissue dies. In a controlled form this effect is utilized in cryosurgery to destroy unwanted growths and cancers. Even more unpleasant effects are caused if moist, bare flesh is held in contact with a very cold surface, for example an uninsulated pipe carrying liquid nitrogen. The moisture on the skin is frozen hard to the surface and it may be impossible to release the skin without tearing or cutting off the frozen layer. Non-absorbent clothing should be worn when handling cryogenic liquids and care taken to ensure that any spilled liquid cannot be trapped inside shoes. Gloves should be dry, non-absorbent and loose-fitting so that they could be removed rapidly if liquid got inside. Should a cold burn occur, flowing cold water should be used to thaw the affected area.

3.3.2 Oxygen Deficiency, Anoxia or Asphyxiation

It is only necessary for the oxygen content of breathing air to fall a few percent below its normal value of about 20% for bodily functions, both mental and physical, to be adversely affected, hence the use of oxygen breathing sets for climbing mountains and high altitude flight. Reduction of the oxygen level towards about 14% causes anoxaemia which is characterised by an increase in pulse rate, laboured breathing and difficulty in concentration. At oxygen levels between 14 and 10% the victim is still conscious but muscular effort causes rapid fatigue and mental processes such as co-ordination and judgement

deteriorate. When the oxygen concentration falls below 10% there is a severe risk of asphyxiation and possibly permanent brain damage. By the time the victim realises that something is wrong it may be too late for him to save himself as his muscles will be unable to function and allow his escape. If the oxygen level falls below 6% death is virtually inevitable - apparently painless, but nonetheless permanent! It is, in fact, surprisingly easy to achieve such low oxygen concentrations. Inhaling just a few breaths, or even one deep breath of pure nitrogen, or any other inert gas, can flush the oxygen out of the lungs and the loss of muscle function can prevent them refilling even if the victim is removed from the inert atmosphere. Some form of rapid resuscitation would be necessary to restore oxygen to the lungs and allow possible recovery. A typical scenario for such an accident is where someone opens and inspection hatch in a nitrogen-purged vessel, puts his head inside to "take a quick look" for something only to collapse within a few seconds because his lungs have become filled with nitrogen. Little or no warning is given by the onset of this form of anoxia, unlike the gradual loss of breathable air that takes place in a sealed volume when the oxygen is not replaced.

There are two important areas in which the effects of anoxia can be avoided. Firstly, it is necessary to be able to detect the presence and extent of regions of low oxygen concentration. Oxygen monitors have replaced the traditional canary for this purpose and used correctly they are invaluable. Care is, however, needed in their location. If, for example they are placed too high up they will not register a dangerous loss of oxygen at working head height. Placed directly over a nitrogen vent or on the floor below an outlet they will trigger prematurely. Such false alarms are likely to lead to distrust or complacency that could prevent operatives from reacting to a truly dangerous situation. Pits and ducts are particularly hazardous as cold gasses tend to sink and accumulate at low levels. When using liquid nitrogen it is essential to maint in a flow of fresh air, often simply by opening the appropriate doors and windows, to prevent the build up of an inert gas.

The second area involves the provision of the appropriate equipment for dealing with an emergency. Particularly important is an advance evaluation of the likely mode and extent of a possible spillage and the measures that should be taken to minimize its effect. For example, evacuation routes should be marked and kept clear. Breathing equipment should be kept handy and personnel properly trained in its use so that they could reach safety and/or effect rescue even in the event of a large spillage and severe nitrogen build-up. Alternatively, the availability of a breathing set could allow someone to remain safely in the affected area to permit rapid remedial action that could prevent a small incident from becoming a major accident. Thus, although automatic shut-down of pumps and closure of valves should be designed into a liquid handling system wherever possible, the ability to close back-up valves manually could also be an advantage in some situations.

STORAGE AND TRANSFER OF LIQUID NITROGEN

Heat-Transfer into Cryogenic Liquids

Energy has to be expended in liquefying cryogenic fluids such as nitrogen and heat influxes need to be reduced as far as possible in order to minimise the rate at which it re-evaporates. It is important to realise that even after a cryogenic fluid has absorbed enough heat to overcome the latent heat of vaporisation, additional thermal energy is needed to warm up the gas. Furthermore, the amount of "sensible heat", as it is called, required to warm evaporated nitrogen gas to room temperature is approximately equivalent to the latent heat. In good cryogenic design practice this sensible heat is used to cool radiation shields, entry pipes and other sources of heat-inleaks and thus reduce the net heat flux that is absorbed by the latent heat.

Insulation Systems

A schematic liquid nitrogen storage vessel is shown in Fig. 4, and there are three mechanisms by which heat reaches the cryogenic fluid: conduction, radiation and convection. Consider first conduction. This comes mainly from from heat flowing along the load-bearing supports and connecting pipes and it is minimised by using thin sections of materials with low thermal conductivities such as glass reinforced plastics and cold-worked stainless steels, etc. Many non-metallic materials used for thermal insulation at low temperatures are in the form of finely divided powders, fibres, films or foams and their low conductivities arise not only from the inherent low conductivity of the material, but even more so, from the poor thermal contact between adjacent particles or layers. Further improvements can be achieved in powdered or fiber insulation systems by removing the gas from between the layers and so cutting down convection losses. In the case of insulating foams, it is important to appreciate the role played by the gas or vapour trapped in the cells. If the blowing gas has high melting or boiling points it may be possible to solidify this gas at low temperatures, reduce convection within the cells and thus improve its insulation value. However, if the cells are not completely closed, gas or vapour may permeate from the warm to the cold faces. Not only will this lower the efficiency of the insulation but permeation of water vapour will break down the cell structure by cyclic freeze-thaw action. As noted earlier, an even more serious problem can be caused by the permeation of air through imperfect foam insulation surrounding liquid nitrogen cooled surfaces as this can lead to preferential condensation of liquid oxygen and the creation of a potential combustion hazard. The solution to both of these problems is to provide an efficient vapour barrier on the warm side of the foam to prevent the ingress of gas or vapour, and this also helps to minimise icing problems. Closed cell foams are widely used for the thermal insulation of liquid nitrogen and other cryogenic systems. They are relatively cheap, efficient and easy to apply, some being foamed in situ. Other types of foam, particularly the extruded type of polystyrene slabstock, have good load bearing characteristics - in general the strongest foams have the highest densities and the highest conductivities.

Radiation, particularly the infra-red component, is reduced by the use of heat-shields, which are either actively cooled by contact with the evaporated, cold gas or act passively by increasing the number of radiating layers between ambient and and cryogenic temperatures. Absorption of radiation at the liquid surface is sometimes reduced by a layer of floating spheres called Froffels which reduce the area of liquid that "sees" higher temperature radiation. In the most effective systems of all, the super-insulants, thin metallic films intercept the infra-red radiation and chemical getters are use to soak up any residual gas.

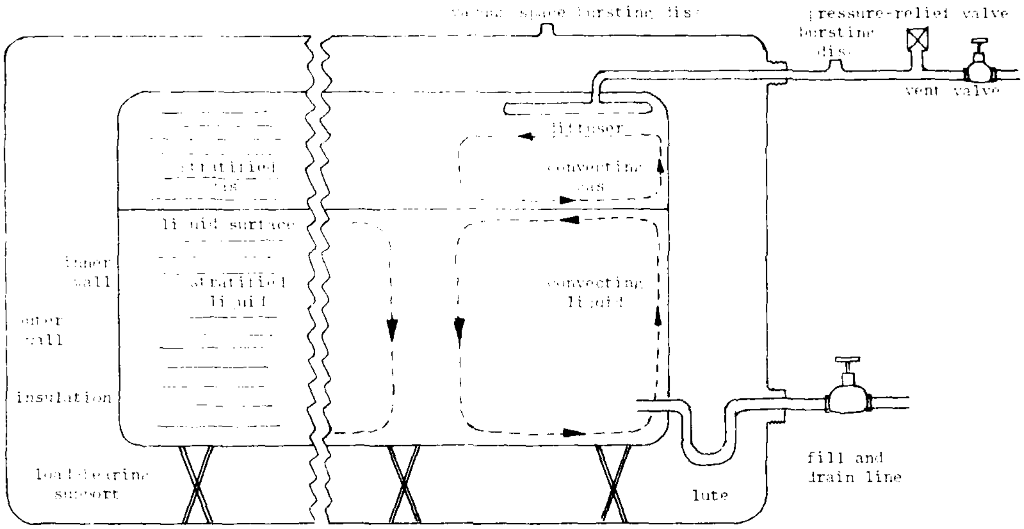


Figure 4 Schematic Representation of Aspects of Liquid Nitrogen Storage

4.2 Storage of Liquid Nitrogen

Storage vessels for cryogenic liquids such as nitrogen are not designed to be full of liquid and about 10% of the total volume, called the ullage space, is left above the liquid surface. This space also allows liquid to separate out and settle as the vessel is filled and in a typical transfer, once the vessel is about 90% full, liquid appears in the gas stream venting from the vessel indicating transfer is effectively complete. Even with an efficient insulation system, there is always a net influx of heat reaching the cryogenic fluid in its storage vessel and this evaporates gas which collects in the ullage space. If the heat influx is minimal, stable stratified layers build up in both liquid and gas with density gradients that tend to oppose any natural convection, as inferred on the left hand side of Fig. 4. For larger heat influxes the gas and liquid in contact with the wall are warmed causing them to rise and set up separate convection systems in both the liquid and the gas. Consider first the gas. The walls are hotter than the gas and so absorb some of its sensible heat, thus becoming cooled. Correct design should enable all of the incoming heat flux reaching the unwetted wall to be absorbed by the cold gas so that there is no heat flow down to the wetted walls where it would have to be absorbed by the latent heat of the liquid. The warming gas rises by convection in the boundary layer adjacent to the walls and falls again in the centre to flow outwards across the liquid surface sweeping with it the cold evaporating gas, so completing the convection cycle, as indicated in the right hand side of Figure 4.

4.2.1 Storage Instabilities

Similar convection cycles exist in the liquid, with upward flow in the boundary layer at the walls and then across the surface where it absorbs heat from the counter-flow of gas and evaporates from the surface of the superheated liquid. This surface evaporation, or boil-off as it is often called, has an irregular nature and takes place in cells whose locations move over the surface. If, however, the liquid is left undisturbed for long periods, the boil-off rate decreases and a stable layer of highly superheated liquid develops on the surface. When subsequently disturbed, this superheated layer evaporates suddenly, leading to a rapid increase in the boil-off rate and a rise in pressure. In smaller-sized storage vessels the temperature of this superheated layer can sometimes rise by up to 40 K before explosive boil-off takes place. Condensation of liquid oxygen or argon in the surface layer can take place if air can leak into the vessel and, as these liquids are both hotter and denser than liquid nitrogen, rapid boil-off occurs if the surface layer is disturbed. It is, in fact, considered good practice to stir liquid nitrogen slowly to prevent the build-up of unstable stratified layers.

4.2.2 Provision of Relief Valves and Bursting Disks.

In Table 1 it was noted that if 1 litre of liquid nitrogen was evaporated and warmed to room temperature and 1 atmosphere pressure it would create approximately 680 litres of gas. If such evaporation were to take place in a enclosed volume the resultant pressure would thus increase to over 600 atmospheres should the structure be strong enough to withstand such a pressure. In practice no storage vessels, transfer lines or other components would be stressed to this level and they would therefore rupture, possibly explosively. To prevent such a hazard, enclosures that could possibly become over-pressurised have to be fitted with relief valves and bursting disks set to trigger and vent the gas safely. It should be noted that the capacity of these items needs to be adequate to cope with the maximum gas flow rate and that the bursting disk should be fitted between the enclosure and the relief valve. Vacuum spaces between the inner liquid container and the external shell must be fitted with bursting disks as a guard against sudden failure of the inner container and consequent ingress of liquid into the insulation. One spectacular rupture of a cryogenic pressure vessel not fitted with a relief valve occurred in Apollo 13 on its way to the moon when an electric heater was accidentally left on in the titanium alloy liquid helium

storage vessel. Other more common causes include the blockage of liquid hydrogen and helium storage vessels by the condensation and solidification of air and the plugging of liquid nitrogen vents and lines by condensed and frozen water vapour. The lute shown in Fig. [illegible] fitted in the fill and drain line between the inner vessel and the valve helps to prevent localised evaporation of liquid from the warm side and the possibility of blockage due to the build-up of impurities such as dissolved water vapour and carbon dioxide.

4.3 Transfer of Liquid Nitrogen

4.3.1 Removal of Liquid from the Storage Vessel

There are three principle methods used to remove liquid from the storage vessel (1) self pressurization of the inner vessel, (2) external gas pressurization and (3) pump transfer.

The liquid flow rates obtainable with self pressurization are relatively low and this technique is most frequently used for smaller sized vessels and laboratory scale applications. Some of the liquid is removed from the storage vessel and passed through an external vapourising coil where it evaporates, expands and causes the pressure to increase. This warm gas is fed back into the storage vessel through the diffuser which, together with stratification in the gas prevents the warm gas flowing directly into contact with the liquid and recondensing.

External pressurization can utilise either the same gas as that liquefied in the storage vessel, or a separate, often non-condensable, gas. Considerably higher transfer rates can be achieved by external pressurization together with rapid response times. In the Douglas Aircraft Company 4ft Blowdown Cryogenic tunnel, liquid nitrogen from a 9000 gallon capacity run tank was pressurised to [illegible] psia using compressed air stored in separate tanks. Transfer rates of [illegible] litres/second ([illegible] gallons/second) of liquid were achieved giving a maximum run time of the order of 30 seconds.

Both the 0.3-m TCT and NTF at NASA Langley used pumps to transfer their liquid nitrogen, 3 pumps being run in parallel when the maximum flow rates of about 450 kg/sec ([illegible]) litres/sec) are needed by the NTF. It should be noted that a Net Positive Suction Head (NPSH) must be maintained at the pump inlet if cavitation is to be avoided. Furthermore as the evaporation rate during liquid transfer is too low to maintain the pressure in the ullage space above atmospheric, nitrogen gas has to be returned to the ullage space to prevent possible collapse of the inner vessel.

4.3.2 Transfer Lines

As noted earlier structures with low thermal mass cool more rapidly and evaporate less cryogenic liquid than those with larger thermal masses and this is one factor that has to be taken into consideration in deciding whether to insulate transfer lines or to leave them bare. When liquid oxygen or pressurised liquid nitrogen is passed through an uninsulated pipe, frost builds up on the outside and tends to insulate it by preventing convective cooling by the air. If, however the nitrogen is subcooled, condensation of liquid air tends to wash away the frost and heat losses are higher. Nevertheless short lengths of bare pipe are often used to transfer liquid nitrogen from delivery tankers to small storage vessels as they are cheaper and less cumbersome than insulated lines. For longer runs and permanent installations transfer lines are, however invariably insulated. An evacuated double walled construction, with or without powder or superinsulation, is usually favoured for the larger and longer lines and, as noted earlier some form of expansion joint has to be provided to prevent the build up of tensile stresses on the inner pipe during cool-down. Flexible foams, with suitable vapour barriers to prevent [illegible] condensation are frequently used for shorter, smaller runs.

4.3.3 Liquid Transfer

In a perfectly insulated, pre-cooled pipe cryogenic fluid would be transferred as a single phase liquid, but in most practical cases some degree of two phase flow is usually present. This can take many forms depending on whether the pipe is horizontal or vertical, the mass flow rate, pressure drop across the line and heat inleaks to the line. In general, stratified flow with the liquid at the bottom of a horizontal pipe and vapour above it occurs at low flow rates, but at higher flow rates, shear between gas and liquid sets up waves or plugs which can completely fill the pipe with liquid. Under some circumstances annular flow occurs and this can be beneficial if it can be arranged in such away that the gas is on the outside completely surrounding a central core of liquid, as in this case heat inleaks from the pipe walls will be absorbed by the sensible heat of the gas not the latent heat of the liquid.

During initial cooldown the first liquid introduced into a warm pipe evaporates on contact with the warm sides. This gas then flows ahead of the advancing liquid front precooling the walls as it progresses towards the outlet, a process that can often take a surprisingly long time. Increasing the liquid delivery pressure can be an expensive way of speeding up the process as less of the sensible heat of the gas is used in precooling the pipe. Furthermore, as the evaporated gas occupies a much greater volume than the liquid, gas velocities can be very high and frequently the flow is choked at the exit during practically the entire cooldown and leaves at sonic velocity. If, however, the flow resistance in the pipe is large it may be impossible to make the liquid front advance more than partially along the pipe such that liquid never emerges from the other end and a zero delivery condition is obtained. The usual solution to such a problem is to modify the line by installing a sufficient number of intermediate venting points to allow the liquid front to be advanced progressively by venting from these intermediate points until liquid emerges and then moving on sequentially to the next vent point. Unpredictable two phase flow through the liquid nitrogen injectors of a cryogenic wind tunnel can also create problems with its temperature control, particularly if the condition does not occur evenly with all injection positions. One design that overcomes this problem is to feed all injectors from a circular "ring-main" of liquid as this prevents vapour building at any particular location.

Control of nitrogen flow through the injectors is achieved using servo-controlled valves, digital valves being used in the 0.3-m TCT but the more conventional gate and globe valves being preferred for the ETW. Rapid and accurate control of the liquid flow is obtained when the system is cold, but care should be taken during cool-down to prevent rapid opening or closing of valves that allow liquid to enter warm areas. The sudden build-up of pressure from the vaporising liquid could lead to pressure surges and even flow reversal, with the risk of damage to pumps and other equipment in the line. Even emergency vent or stop valves should be arranged so as to operate over a few seconds rather than slamming shut.

5. STRENGTH AND TOUGHNESS OF METALS AT LOW TEMPERATURES

One of the principal design requirements of any piece of equipment is that it should have adequate stiffness, strength and toughness to withstand safely any load or stress that may be applied to it. Operation at low temperatures effectively increases the requirement for adequate toughness at the operating temperature, as virtually all materials are both stiffer and stronger at low temperatures than an ambient. A load-bearing structure must, therefore, be able to cope with not only the static and dynamic stresses which can be predicted for normal operation, but also the thermal shocks it may be subjected to on cool down, the thermal stresses induced by differential expansion during warming and cooling cycles, as well as the accidental overstresses or impact loads that it may receive in the presence of the scratches and dents it is liable to suffer during service.

Most materials are designed to operate within their elastic limits and typical stress and deflection formulae require the use of appropriate values for the elastic constants such as the Youngs, Shear and Bulk moduli and Poissons ratio. Fortunately, the elastic constants are relatively insensitive to structure variations such as changes in grain size, the degree of cold working, heat treatment and small compositional variations etc., while decreasing the temperature in general increases Youngs modulus by about 10% between 300 K and 80 K. Accuracies greater than about 1% are rarely required in the calculations normally used to avoid buckling failure (elastic instability) or excessive elastic deformation (jamming) and thus values taken from the literature can be used with a reasonably high degree of confidence. The design problems created at ordinary temperatures by the relatively low modulii of aluminium alloys when compared to either austenitic or ferritic steels are also encountered at low temperatures where stiffness is important, for example, where shell bending is a significant design limitation, as in a column subjected to a lateral air flow loading. In such cases, the higher modulii offered by, for example, the austenitic stainless or 9% nickel steels would allow either stiffer structures for the same section or thinner sections for the same stiffness.

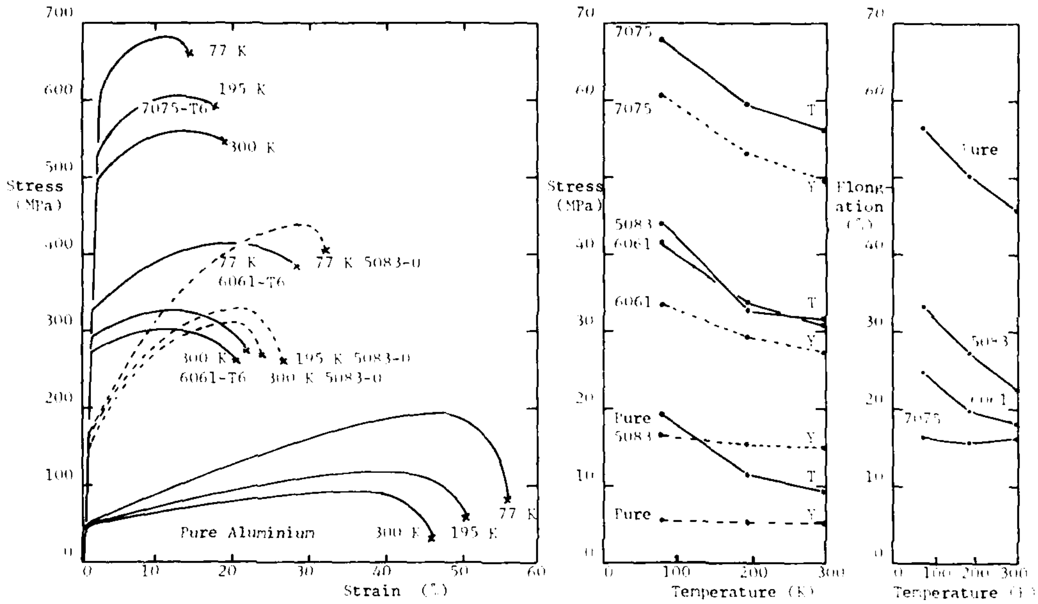
Yield and plastic deformation in metals are processes strongly influenced by their structure and condition to such an extent that accurate predictions are difficult and experimentally determined data invaluable. General classification of their properties is best started by considering their crystal structures, most metals and alloys having face-centred-cubic, body-centred-cubic or hexagonal-close-packed lattices. Of these the face-centred-cubic metals are greatly to be preferred for low temperature use as almost without exception their strengths, ductility and toughness all improve as the temperature falls, thus making them ideal for cryogenic applications. F.c.c. copper-, nickel-, and aluminium-based alloys, together with Invar and the austenitic stainless steels are, in fact, the metals most widely used for the construction of equipment operating below about 150 K. Of the hexagonal-close-packed metals only magnesium and titanium are used in significant quantities below room temperature, the high specific strengths offered by titanium alloys being particularly attractive for certain specialised applications in the aerospace industry.

It is the body-centred-cubic group of metals that offer the greatest challenge but which constitute the greatest risk as they almost all undergo a transition from ductile to brittle behaviour at some temperature, usually below ambient. Furthermore, small changes in their chemical composition, grain size, the degree of plastic constraint brought about by a notch or flaw, and even the rate at which a load is applied, can all have a marked effect on the delicate interrelationship between strength, toughness and the temperature at which the ductile-to-brittle transformation occurs. As however, the economically irreplaceable ferritic steels have b.c.c. structures, their use at low temperatures cannot be precluded and it is necessary to define the temperature and stress limits to which a certain grade, thickness and condition of steel may be safely used. These limitations are traditionally laid down by codes of practice issued by independent bodies such as the American Society of Mechanical Engineers, government agencies such as the British Standards Institution, local or national insurance agencies or even state regulatory authorities, and there are very few load bearing structures which can be built without conforming to one or more such codes. There is also, however, an increasing and very welcome tendency towards backing up these codes by a scientifically rigorous failure analysis based on the concepts of fracture mechanics - a study of the resistance offered by a material to the continued propagation of a crack nucleating in the vicinity of a sharp crack. Such analyses are also applicable to high strength alloys with f.c.c. and h.c.p. structures, as well as to the rate at which cracks propagate during fatigue and so constitute a powerful analytical technique which the aerospace industry in general was quick to develop and exploit.

The mechanical properties of materials at low temperatures are considered in detail in References 6, 7, 14 and 15, while data is presented in References 16 to 19.

5.1 Face-Centred-Cubic Metals and Alloys

Although some copper and nickel based alloys are used for particular applications in cryogenic wind tunnels, the quantities involved are small and they are best considered in the next lecture in the context of their use in model construction. It is only aluminium alloys and the austenitic iron-based alloys that are likely to be used in significant quantities.



(a) Stress-Strain Curves (b) Stresses vs Temperature (c) Elongation

Figures 5(a), (b) and (c). The Mechanical Properties of Aluminium and its Alloys at Low Temperatures.

5.1.1 Aluminium Alloys

It is instructive to start by considering the properties of pure aluminium because it shows very clearly the basic characteristics of f.c.c. metals which make them so useful at low temperatures. In Fig 5(a) a series of engineering stress-strain curves are shown for aluminium and some of its alloys tested at and below 300 K. The following features should be noted from the curves for pure aluminium.

i) Yield is a gradual process and the yield stress is only a weak function of temperature.

ii) The strain hardening rate (slope of the stress-strain curve after yield) , the ultimate tensile stress (maximum point in the curve) and the total plastic elongation all increase as the temperature falls. Thus the metal becomes both stronger and more ductile at low temperatures essentially because it is able to accommodate a greater degree of strain hardening before the onset of necking (plastic instability).

iii) The large drop off in measured stress between the onset of necking and final failure is indicative of a large reduction in area and hence a very ductile type of fracture at all temperatures.

In Figs 5(b) and (c) the data is cross-plotted to show more clearly the temperature dependence of the yield and tensile strengths and the elongation. It is the combination of increase in ductility and tensile strength, together with the relative temperature-insensitivity of the yield stress that is the definitive characteristic of face-centred-cubic metals and alloys which makes them so eminently suitable for use at low temperatures. It is brought about by their ability to slip and deform to prevent the build-up of high stress concentrations at the tips of cracks and flaws.

Pure aluminium has high electrical and thermal conductivities and it has replaced copper in many instances where these characteristics are required. Its alloys are widely used where moderately high strengths combined with high toughness and low density are necessary, such as in road and rail transporters for liquid gases, as well as in static liquid storage tanks. Aluminium alloys may conveniently be divided into two groups according to the basic metallurgical strengthening mechanism involved: (1) the solution-hardened alloys, which are very ductile but only moderately strong in the annealed state (although their strengths can be improved by cold working), and (2) the precipitation-hardenable types, which can be heat treated to give considerably higher strengths.

Of the solution-hardened types, those containing manganese as the main alloying addition (3000 series) have only moderate strengths, but they are very ductile and hence easily formed. Type 3003 is used for tubes, bends, junctions, plate fin heat exchangers, tube plates and trays, as well as in distillation columns and many other applications. Their role in heat exchanges arises largely because they can be dip-brazed in molten salt baths using aluminium-silicon eutectic alloys. They can also be extruded and cut with roller cutters, characteristics which are advantageous for volume production. They can be cold-worked for higher strengths, but, as they are so often used in the welded or brazed condition where these advantages would be lost, it is more usual to use one of the higher-strength alloys where necessary.

The aluminium-magnesium alloys (5000 series) have higher strengths than the 3000 series and they are widely used for the construction of land-based storage tanks, road and rail transporters and for the primary containment of liquid natural gas in LNG ships. A series of stress-strain curves from tests at

300, 195 and 77 K on a 5083 alloy is also shown in Fig 5(a) It can be seen that the yield strengths are higher than those of pure aluminium but still relatively independent of temperature. The strain hardening rate is also higher and becomes still more so at lower temperatures so that both tensile strength and elongation improve at low temperatures and thus the alloy is ideal for low temperature use. Type 5083 alloy is, in fact, the largest-tonnage alloy in cryogenic service largely due to its combination of moderately high strength with excellent weldability. Gas-metal-arc and tungsten-metal-arc systems have been used to weld plates up to 175 mm thick; even in the as-welded condition its full strength is retained thus giving it an advantage over the higher strength 2000 and 7000 heat-treatable alloys if post-weld heat treatment is not possible. Additional strength can be achieved in the 5000 series alloys by cold rolling but the consequent loss of ductility is not always acceptable. Most of the internal structure of the NTF is fabricated in 5000 series alloys. The contraction, test section, high speed diffuser and upstream nacelle are made from welded 5083, as in the non-cryogenic operating mode the temperatures of these parts does not exceed 66 C (150 F). This is the maximum temperature at which 5083 can be operated continuously in a highly stressed state while avoiding the possibility of grain-boundary stress corrosion. Due to the increase in temperature of the gas stream created by the power of the fan, which can be as much as [illegible] F) at the high power ambient temperature operating condition, those sections between it and the cooling coil, the downstream nacelle, shrouds and rapid diffuser, are made of type 5454. This alloy can be used safely at the higher temperatures but, as its yield stress is about 50% of that of 5083, thicker sections are necessary.

Aluminium-magnesium-silicon alloys (6000 series) have the lowest strengths of the heat-treatable types and, in general, they are the only ones used outside the aerospace industry. Type 6061 in the T6 condition is stronger than the 3003 and 5083 alloys but its strength in the as-welded condition drops below that of the solution hardened alloys. It is generally available in the forms of pipe, pipe fittings, extruded tubing and other shapes. Stress-strain curves for 6061-T6 are also shown in Fig 5 (a) and it can be seen that their shapes differ from those of pure aluminium and the solution hardened 5083. The yield stresses of 6061-T6 are higher and more temperature dependent and the strain hardening rates are lower. The tensile strengths do not greatly exceed the yield strengths and elongations are smaller at all temperatures than for 5083. Nevertheless, the mechanical properties of 6061-T6 make it suitable for cryogenic applications and it was used for construction of the pressure shell and internals of the NASA LaRC 0.3-m TCT.

The aluminium-copper alloys (2000 series) have higher strengths than the Al-Mg-Si types but their toughness, especially their notch toughness, begins to fall seriously at low temperature and they are not widely used. Moreover, they are often considered to be less easy to weld reliably. Nevertheless, welded type 2014-T6 was employed in the construction of the liquid-oxygen and liquid-nitrogen fuel tanks for the Saturn V Rocket where its high strength/weight ratio proved advantageous.

The final series of stress strain curves in Figure 5 (a) is for one of the very high strength aluminium-zinc-magnesium heat-treatable alloys, 7075-T6. As may be seen, very high yield strengths are attainable at and below room temperature. However, it is also apparent that the ductility, which is already rather low at room temperature, falls even further at low temperatures. If the samples were notched and/or loading rates higher, the picture would appear even blacker as these very high strength alloys have low notch-toughness and are thus rarely used below room temperature. They do, however, provide a convenient example of how a very high strength alloy, even with an f.c.c. structure, can have such a low fracture toughness as to make it necessary to use fracture mechanics analyses for safe design. Even though the alloy does not fail by cleavage, slip is so inhibited by the metallurgical process used to create its high strength that it is no longer able to deform easily and reduce stress concentrations at the tips of cracks and flaws.

5.1.2 Austenitic Stainless Steels

This is one of the most important class of materials used in the construction of equipment for operation at low temperatures. The face-centred-cubic gamma phase of iron is normally only stable at high temperatures, but the addition of alloying elements such as nickel, manganese, carbon and nitrogen suppresses the gamma-alpha transformation and enables the austenitic gamma phase to be retained to room temperature and below. The gamma structure is, however, only metastable and under certain conditions of stressing and/or cooling a partial transformation to martensite can take place in some of the less highly alloyed steels such as type 304. Two martensite phases are formed having h.c.p. and b.c.t. structures respectively, and it is the b.c.t. form which leads to an increase in strength but loss of toughness in the transformed state. Furthermore, b.c.t. martensite is ferromagnetic and its presence is a severe disadvantage in applications where magnetic fields are present. Finally, to make matters even worse, the transformation is accompanied by a volume expansion which can spoil the fit of accurately machined components such as shafts and flanges.

In general, the most stable steels are those with the highest nickel contents such as the 25-Cr, 20-Ni type 310 wrought alloy and the analogous casting alloys CF20 and Fromarc-55. One disadvantage of 310 is its rather low yield strength of about 200 MPa at room temperature, but if some loss of ductility can be tolerated this may, however, be raised to about 500 MPa by cold working without either a significant drop in toughness or transformation to martensite. Because of its high nickel content type 310 is more expensive than other 300 series stainless steels and it is somewhat more difficult to obtain in a wide range of product forms than the more popular alloys. In most other 300 series austenitic stainless steels some degree of martensitic transformation may be induced by stressing or thermal cycling. The ferromagnetic nature of b.c.t. martensite allows its existence to be established very simply by the use of a small pocket magnet, while a somewhat more sophisticated, and hence expensive, variation on this theme uses a calibrated spring balance to measure the force required to remove a magnet from the surface of the sample.

In a series of experiments carried out by the International Nickel Company, the magnetic permeability of a series of austenitic stainless steels was measured before and after cold rolling at 300K and 77 K. It was found that type 310 showed no transformation while type 301 was strongly affected by both treatments. The samples of 316, 321 and 347 showed an increasing tendency to transform during cold rolling

but were relatively unaffected by thermal cycling. Type 304, one of the most widely available of all the austenitic stainless steels, has the greatest variability in its behaviour because small decreases in the carbon and nitrogen contents can be very harmful as both elements are strong austenite stabilisers. It is therefore worth noting that the recently developed 'Hi-proof' grades of 304, 316 and 347 which contain 0.2% nitrogen to increase their yield strengths by about 70 MPa, will also be very much more resistant to martensite transformation than the normal grades. In contrast the low carbon grades of 304 used to prevent weld decay will be least resistant to martensitic transformation! When the nitrogen bearing grades 304N, 316N and 347N become more readily available in the product forms required, they will offer probably the best combination of properties available for low temperature applications from any austenitic stainless steel and their use should be encouraged. Regrettably, they are, at present, difficult to obtain in small quantities and in forms other than sheet and plate.

A further point worth noting from the results of the International Nickel Company experiments concerns the effect of thermal cycling. If the ferromagnetic nature of a partially martensitic 300 series steel is not a drawback for a particular application which demands good dimensional stability, it is possible to ensure that transformation is complete before final machining. This may be achieved by cycling repeatedly between 300 K and 77 K, if necessary taking measurements after each few cycles, until no further significant dimensional changes occur. Further consideration of dimensional instability, particularly in the context of wind tunnel models, will be given in the next lecture.

Type 304 is the most readily available of the austenitic stainless steels and the low carbon welding grade 304L was used for the outer pressure shell of the NTF. Under normal operating conditions the outer shell is unlikely to be cooled more than a few tens of degrees below room temperature, due possibly to localised degradation of the insulation. Furthermore, should some malfunction lead to the build up of liquid nitrogen inside the shell, the inherent toughness of the austenitic structure ought to ensure that no embrittlement problems would be encountered.

5.2 Body-Centred-Cubic Metals and Alloys

As a general rule metals with b.c.c. crystal structures undergo a ductile-brittle transition which occurs at some temperature which may be above or below room temperature. There are a few exceptions, but for practical purposes the potentially brittle nature of b.c.c. metals at low temperatures puts a severe limitation on their use. However, they cannot be disregarded as they include the whole range of carbon, low-alloy and nickel steels which are economically irreplaceable for the construction of equipment operating at moderately low temperatures. The basic philosophy behind their successful application lies in ensuring that they have adequate toughness at their minimum operating temperature for them to withstand not only their design stresses but also accidental impact and other overloads without failing in a brittle and catastrophic manner.

5.2.1 The Ductile-Brittle Transformation in Ferritic Steels

One manifestation of the ductile-brittle transformation in low-alloy ferritic steels can be observed in the sharp decrease in the tensile elongation that occurs at the transition temperature. A much more realistic indication of the seriousness of the problem is, however, obtained from the tough-brittle transformation measured by the decrease in the impact energy absorbed in Charpy V notch tests carried out over the transition temperature range. For a plain carbon steel the toughness transition takes place at or above room temperature, whereas the ductility transition occurs at some 220 C lower. About half of this drop can be accounted for by the very much higher strain rates involved in an impact test, as ferritic steels are highly strain rate sensitive. Thus in practice ferritic steels should not be subjected to sharp blows or impact loading when they are below their toughness transition. The remainder of the decrease is due to the presence of the stress concentration at the notch root, an indication of the importance of avoiding sharp corners and minimising stress concentrations. Small variations in the depth or sharpness of the notch also account for much of the scatter in the impact energies measured over the transition range. In general most metallurgical and other factors which strengthen the material, e.g. cold work, increased alloy additions, precipitation hardening, etc., also lower its toughness. The only exception to this rule is the action of grain refinement as this increases both the strength and the toughness. Indeed grain refinement is one of the most important methods of obtaining toughness in ferritic steels at low temperatures, and this is achieved in part by increasing the manganese concentration relative to that of carbon, high Mn/C ratios giving finer grained structures. The degree to which the steel is deoxidised, or killed, by the addition of silicon and aluminium is also important, fully-killed steels being tougher, but more expensive, than semi-killed steels. Niobium and vanadium are also added to high grade steels to produce additional grain refinement, while careful control of the aluminium, nitrogen and vanadium concentrations can lead not only to enhanced grain refinement but also to precipitation hardening by their resultant nitrides and carbides.

It is, however, the nickel alloy steels that are most widely used at and below 220 K. In Britain 2.25, 3.5, and 9% Ni steels are readily available and these grades adequately span most required temperature ranges. 2.25% Ni steel is used down to 210 K, particularly for equipment handling liquid propane at 230 K, while 3.5% Ni steel down to 170 K and is commonly specified for tanks, pipes, and other applications involving liquid ethylene, ethane, acetylene and carbon dioxide. It is, in fact, also often employed for higher-temperature applications because the additional safety margins given by its higher toughness compensate for its marginally higher cost compared to 2.25% Ni steel. A 5% Ni steel is also used quite widely in Europe at temperatures down to 150 K, particularly in the fabrication of welded vessels for the handling and storage of liquid ethylene. The use of 9% nickel steel in thicknesses up to 50 mm and at temperatures down to 77 K without post-weld heat-treatment has been allowed since 1962 under ASME code case 1308. This steel is available in both (1) the quenched and tempered, and (2) the double normalised and tempered conditions, (1) having a marginally higher yield stress and lower ductility at room temperature: it is unusual in that post-weld heat treatment actually lowers its toughness and this treatment is therefore not recommended. It is the only ferritic steel permitted for use at liquid-nitrogen temperatures and it is economically competitive for the construction of large storage tanks for liquid nitrogen, oxygen, argon and methane. Its high proof-stress/tensile-stress ratio gives it a distinct advantage if design on the basis of proof-stress such as BS 5500 is permissible, but even when designing to tensile-stress codes

it is still a very economical material. It is readily welded, but fillers with the same composition as the parent metal must not be used as such welds lack adequate toughness. Austenitic 25% Cr-20% Ni consumables give tough welds with expansion coefficients that match those of the parent metal, but whose strengths are lower, whereas the higher-strength Inconel types have mismatching expansion coefficients and this can cause high contraction stresses to be set up during thermal cycling. Thus neither type of electrode is ideal and furthermore their high cost detracts somewhat from the favourable economics offered by the parent metal. It should be noted that 9% Ni steel, like other high-tensile steels, is particularly prone to hydrogen embrittlement and thus precautions have to be taken to prevent hydrogen pick-up during welding or in service. A special high quality version of 9% Ni steel was used for the fan shaft of the NTF. The possibility of using the standard alloy for the pressure shell must also have been considered seriously as it would have been a cost-effective alternative to the 304L stainless steel eventually chosen, the relative availabilities of the quantities and product forms required probably being one of the deciding factors.

5.2.2 Cryogenic Wind Tunnels with Ferritic Steel Pressure Shells

It should be noted that there are in fact a number of cryogenic wind tunnels in operation in which the pressure shell is made of mild steel and similar low alloy steels with tough-brittle transitions near room temperature. These may be divided into two categories, the first being blow-down tunnels or recirculating tunnels with short duty cycles. In these cases the tunnels are lined with a relatively thin layer of some form of durable insulation that can be given a clean aerodynamic profile. The thermal characteristics of the tunnel are analysed to establish that the thermal diffusivity of the insulation is low enough to prevent the walls from cooling significantly during the cold period of the tunnel duty cycle. The second type of tunnel is typified by the tunnel at Tsukuba University, Japan. Here the internal insulation is much thicker and the tunnel operates continuously. Thermocouples are used to sense the temperature of the insulation layer adjacent to the inner surface of the pressure shell and heater tapes are available to provide local heating should it be necessary to ensure that the wall temperature does not fall below its tough-brittle transition.

5.3 Fracture Toughness and Crack Propagation

In most materials the presence of a notch or flaw has an embrittling effect due to the stress concentrating effect at the tip. Modern theories of Linear Elastic and General Yielding Fracture Mechanics (LEFM and GYFM) can relate the fracture strength and critical flaw size to the Fracture Toughness of the material, Kc. In a simplified form the basic relationship is:

$$\sigma_F = K_c \; / \; [\pi a + 0.5(K_c/\sigma_y)^2]^{1/2}$$

where σ_F is the fracture stress, K_c the fracture toughness, σ_y is the yield stress and a is the critical crack length. Note particularly the term $(K_c/\sigma_y)^2$, as it gives an indication of the amount of plastic deformation that takes place in the material ahead of the advancing crack. If σ_y is small, (K_c/σ_y) is large and there is a large plastic zone ahead of the crack tip. Relatively large amounts of energy are absorbed in tearing through this zone and crack propagation is therefore made more difficult. In contrast, if σ_y is large, (K_c/σ_y) is relatively small, the plastic zone size is also small and little energy is absorbed by shear deformation. Furthermore, we have already seen that the yield stresses of many alloys increase quite rapidly as the temperature falls. Thus to maintain the same relationship between fracture strength and critical crack size the fracture toughness would have to increase in proportion to the yield stress. This does not happen in many high strength alloys and as a result the critical crack size decreases and they become increasingly notch brittle. Unfortunately the fracture toughness of a material is not only highly dependent on its physical and mechanical condition but also on its thickness and even sample width. Nevertheless the application of the concepts of fracture mechanics have provided a better understanding of fracture behaviour in high strength alloys and a firmer basis for design to prevent low energy absorbent fracture.

It is convenient to divide materials into the value of the ratio of the tensile modulus to the yield strength, E/σ_y. If E/σ_y is less than 150 the material has such a high strength that critical flaw sizes are low and load-bearing structures must be designed using fracture toughness analyses. If E/σ_y is greater than 150 the material is low strength and only those bcc metals such as ferritic steels that fail by cleavage lack toughness. Medium strength materials falling between these limits at room temperature can become effectively high strength materials at low temperatures because of the rise in their yield stresses. Fracture mechanics analyses are carried out for many of the high strength materials used in various cryogenic wind tunnel applications including the support stings, balances, models and other components that are highly stressed at cryogenic temperatures. Fracture toughness is considered further in the next lecture and selected values for Kc at 300 and 77K are given in its Appendix for many of the alloys likely to be of use for these applications.

5.4 Time-Dependent Failure

As has been shown, the fracture stress of a material is strongly influenced by the presence of cracks and flaws. There are three principle mechanisms by which such cracks may form or intensify during service: (1) fatigue, (2) corrosion (especially-stress corrosion and corrosion-fatigue), and (3) hydrogen embrittlement. None of these is a specifically low-temperature phenomenon, indeed the fatigue lives of many metals increase considerably at low temperatures, while the rates at which most corrosion reactions take place drop rapidly as the temperature falls - rather they increase the probability of unstable failure under service conditions which would normally be considered satisfactory. Their effect is the result of one or more of the following factors: (a) they lower the toughness of the material, (b) they provide a mechanism whereby a crack sharpens and increases the degree of stress concentration, or (c) they allow a sub critical crack to grow at stresses below the gross yield stress until it reaches the critical length required for unstable propagation.

5.4.1 Fatigue and Thermal Fatigue

Fatigue failure occurs in materials subjected to cyclic or fluctuating stresses which may or may not be superimposed on static applied stresses. Failure under such loading conditions can take place at stresses which are very much lower than the tensile or yield stresses even in materials which are normally

considered to be tough and ductile. Fatigue must therefore be considered as a possible mode of failure in any piece of low-temperature equipment subjected to cyclic loading or vibration (for example, pumps, motors and turbines), or to periodic changes in pressure (transfer lines, storage vessels, and other process plant). The severity of the problem may be indicated by the estimate that about half the failures encountered in general engineering practice are caused by fatigue. Fatigue tests carried out at low temperatures have shown that fatigue lives of most metals rise considerably as the temperature falls. It has already been demonstrated that the tensile stresses of most metals increase as the temperature is lowered and it has been found that there is a strong correlation between fatigue strength and tensile strength; indeed, experiments have shown that in some metals the ratio of the endurance limit at 10^5 cycles to the tensile stress is virtually independent of testing temperature.

Thermal fatigue is of particular relevance to cryogenic plant, such failures having occurred in regenerators after a large number of temperature reversals, and in heat exchangers and other components after a relatively small number of warming and cooling cycles caused by plant shut-down. The basic cause of this type of fatigue is the high stresses and strains that can be set up during thermal cycling if temperature gradients are non-linear or if free expansion and contraction are restricted by external constraints. In this type of low-cycle, high-strain fatigue, small amounts of plastic deformation take place during each loading cycle and cumulatively lead to failure. Such failures were in fact encountered in the early operation of NASA LaRC 0.3-m TCT where "spoke-like" aluminium struts were rigidly attached to the tunnel pressure vessel and to central "hub-like" structures. Subsequent redesign using PTFE cushioned "T" slots at the central hub attachment points allowed free thermal expansion of the spokes and elimination of the stresses that caused thermal fatigue.

Pre-existing flaws, notches, cracks, badly radiused corners and other surface defects have a strong influence on fatigue lives, causing them to drop sharply at all temperatures even in materials which are not normally considered to be notch sensitive. This is usually a result of the increase in stress intensity brought about by the sharp fatigue cracks and it is particularly severe in high-strength aluminium alloys, titanium, and stainless steels which are known to be notch sensitive. As noted earlier, it is possible to apply the concepts of fracture toughness to crack growth under cyclic applied stresses and many data compilations (e.g. Ref. 14) show the relationship between crack growth rate da/dN as a function of stress intensity factor range ΔK. Predicted component lives are then obtained by calculating how many cycles are required to increase the flaw size from its initial to the critical value. In general, fatigue crack growth rates decrease at low temperatures for most metals normally used for the construction of cryogenic equipment. In contrast they increase for ferritic steels at temperatures below the ductile-brittle transition.

Corrosion fatigue can be a problem with some low temperature equipment particularly if it is frequently cycled between low and ambient temperatures. In the presence of even mildly corrosive environments large reductions in the endurance limits can occur even though the amount of metal corroded is negligible. Some aluminium alloys are especially prone to corrosion-fatigue, ordinary moist air causing some deterioration, while salt-laden atmospheres are particularly harmful. Premature failure has been known to occur in air separation plants located by the sea or near chemical plants and if such conditions are liable to be encountered it is necessary to apply a protective coating to the metal or to specify a material such as stainless steel, which is less susceptible to this type of failure.

5.4.2 Corrosion and Embrittlement

These are two mechanisms by which failure can occur without warning long after the initial application of the stress and they can cause failure at low temperatures even though the actual corrosion or embrittlement is more likely to have taken place at or above room temperature. Stress-corrosion resulting from internal residual stresses is liable to occur in brass, aluminium, magnesium, titanium, and steel as well as some non-metals. It is usually prevented by annealing at a temperature high enough to remove the residual stresses without weakening the material. Hydrogen embrittlement is a particular problem in high-strength steels such as 9% Ni steel. The hydrogen is usually absorbed during pickling and plating processes or during welding, and, although the hydrogen can sometimes be removed from steels by baking at 350 C, it is better to prevent its initial pick-up where possible.

6. STRENGTH AND TOUGHNESS OF NON-METALS AT LOW TEMPERATURES

Non-metallic materials have much more complex structures than metals and the amorphous and microcrystalline structures typically found in glasses and ceramics almost invariably make them brittle because they are unable to accommodate the plastic deformation needed to relieve the high stress concentrations which build up around small flaws. They are thus much stronger in compression than in tension but are rarely used in the bulk form even under compressive loadings because their poor thermal conductivities and consequent liability to thermal shock make them liable to shatter. However, in the finely divided form of fibres, powders, films, foams and expanded granules they are widely used for thermal and electrical insulation at low temperatures.

6.1 Ceramics and Glasses

Glasses and ceramics have amorphous structures and they are unable to deform plastically and relieve stress concentrations caused by microcracks in their surfaces. They fail in tension at relatively low stresses at all temperatures and their use in bulk form at low temperatures is limited. Glass Dewar flasks are, however, still used for storing small quantities of cryogenic fluids and large plate glass windows are employed as viewing ports in cryogenic bubble chambers. Careful thermal annealing to remove surface cracks and residual stresses is essential for these applications, while thick sections have to be cooled extremely slowly to avoid failure due to differential contraction or thermal shock. Ceramics and glasses are stronger in compression than in tension because the microcracks are propagated by tensile stresses and residual compressive stresses are often induced in the surfaces of glass plates to toughen them. In a similar manner concrete structures, which are also brittle in tension, can operate satisfactorily at low temperatures if kept in compression and large liquid-natural-gas storage tanks have been constructed in which the concrete is maintained in compression by steel reinforcing rods placed in

tension around the warmer outside of the tank. The liquid nitrogen storage tanks for the University of Tsukuba cryogenic wind tunnel are also made of concrete lined internally to minimise the evaporation rate and keep the tension rods in the warm part of the concrete. For applications such as the floors of loading bays for road tankers transporting cryogenic liquids, it has been found that high alumina cements such as Ciment Fondue are much more resistant to shattering by thermal shock than is ordinary Portland cement.

6.2 Thermoplastics and Thermosets

Polymeric materials can be divided basically into two structural categories: the thermoplastics and the thermosets. The long chain molecular structures of thermo-plastics give them mechanical properties which are strongly dependent on the temperature and rate at which they are stressed. Furthermore, an increase in their intermolecular forces over a temperature range known as the glass transition, which may be above or below ambient, means that most thermoplastics undergo a reversible transition to a glass-brittle state in which they are unable to deform plastically. As their glass transition temperatures are all above 150 K there are no thermoplastics which exhibit any really significant degree of ductility below this temperature.

Thermosetting polymers have a network structure which renders them brittle and they are thus rarely used in the unfilled state. However, when combined with suitable fillers their toughness is greatly improved and phenolic-impregnated cloths and papers (such as Tufnol and Paxolin) are particularly useful for the fabrication of load-bearing, electrically-insulating fitments. The inclusion of powdered glass or ceramic powders reduces the brittleness of un-filled resins while the incorporation of glass or carbon fibres and cloths in epoxy resin matrices gives the high performance composites to be considered in section 6.4.

Materials selection becomes even more complicated if these materials are needed in applications where liquid oxygen (LOX) is present, as virtually all hydrocarbon-based polymers are incompatible with LOX and burn violently in its presence. The polysulphides, silicones and fluorosilicones are more LOX compatible, but it is only the fluorocarbons that are completely satisfactory in this respect.

6.2.1 Thermoplastics of Particular Interest for Cryogenic Wind Tunnels

Applications of major interest for wind tunnel models will be considered in the next lecture. Here we will consider thermoplastics in their roles as seals and adhesives. Correctly designed fittings are important if leak-tight joints are to be made at low temperatures. As long as no dynamic stresses are involved, satisfactory seals can be obtained from elastomers, even when they are below their glass transition. In order to achieve this aim, very large compressive strains are imposed at room temperature so that the elastomer is able to exert sufficient force to offset the decrease in load caused by the contraction which takes place as it goes through its glass transition. The most satisfactory results are obtained using confined compression designs in which a follower on one flange squeezes the O-ring into the bottom of a matching groove in the face of the other flange, as well as into the clearance space between groove and follower. The O rings are typically compressed by about 80% of their original diameter and are thus not re-useable.

The fluorocarbon family of polymers, polytetrafluoroethylene (PTFE, TFE, Teflon), the fluorinated ethylene/propylene copolymers (FEP), and polychlorotrifluoroethylene (PCTFE, Kel-F), are the only materials which retain any measurable ductility (approx. 1%) down to 4 K. This is a result of their unique molecular structure in which crystallites are formed having a tight spiral formation of fluorine and chlorine groups which are unable to pack closely together, thus preventing the material from having a strong glass transition. Although these materials are not elastomers, their ability to undergo enough plastic deformation to form a satisfactory seal makes them invaluable for use at temperatures down to 4K. They do, however, suffer from a tendency to cold flow under continuous load, and seals are thus liable to leak unless the load can be increased to compensate for the cold flow. Filled-PTFE compositions have been developed to overcome this problem, glass-fibre being most commonly used for O-rings and gaskets, while graphite, bronze and other powders are also used for bearing applications. Glass fibre improves the tensile and compressive properties of the materials, while the PTFE gives it sufficient ductility to accommodate plastically the strains developed. Furthermore, the thermal contraction of the composite is reduced from the high value characteristic of unfilled PTFE, so that the expansion of the composite is more compatible with that of metals, thus making joint design easier. The confined compression designs of flanges are also to be preferred for use with fluorocarbon seals because they minimise the deleterious effects of cold flow.

In the NASA LaRC 0.3-m TCT many large and small diameter seals are made using "Gortex". This is a low-density form of PTFE created by a proprietary process that involves stretching the material to about 10 times its original length without reducing its diameter. The material has been found to be particularly suitable for the demountable seals on the plenum cover of the 2D test section. Although "Gortex" is not intended for re-use, it has been found that it is not necessary to replace the gaskets each time the cover is opened. An alternative approach is to use spring- or pressure-assisted seals. In spring-assisted seals a metal backbone spring provides the sealing force and helps to compensate for dimensional changes during cool-down, while the PTFE coating forms the actual seal with the mating surface. A "U" shape cross section seal with a type 302 stainless steel spring and PTFE coating was chosen for the NTF, the "U" shape section allowing the use of gas pressure to improve sealing efficiency. It was also found that the surface finish of the mating surface was important, a 0.8 μm (32 μin) RMS finish being acceptable, and that treatment of these surfaces with FEP or TFE tapes or lubricants improved sealing efficiency.

There are many applications in which metal-metal, metal-plastics or plastic-plastics adhesive joints are advantageous. For example, brackets, clips and other attachments can be bonded to pressure vessels without creating the stress raisers that would otherwise be caused by welding or other conventional techniques, while corrosion-free joints between dissimilar metals can be obtained if their surfaces are kept apart by an electrically non-conducting adhesive. At room temperature, adhesives are usually able to deform sufficiently for any stress concentrations to be relieved, but at low temperatures their moduli increase considerably and make this much less likely. Contraction and other stresses have to be minimized

and the key to the successful development of structural adhesives lies in the use of fillers that match the expansion coefficients of the adhesives as closely as possible to those of the substrate and the adherent. They also redistribute thermal stresses throughout the adhesive instead of concentrating them at the adhesive-substrate interface. Even so, the thermal conductivities of most adhesives are low, and temperature differentials between them and metal substrates can cause failure from thermal shock if the glue line is not kept as thin as possible. One way of achieving this is to use a 'structure' or 'carrier' between adherent and substrate. This is usually a thin layer of glass fibre mat which allows the adhesive to penetrate and wet the filaments, thus forming an even bond as well as reducing the differential contraction between adhesive and adherent. It also has the further advantage of reducing creep at ambient temperature in adhesives such as the polyurethane pastes, which in other respects are among the most successful adhesives for low-temperature applications. Other types include the epoxy-nylons, nitrile modified phenolics, epoxy-phenolics, and fluorocarbon-epoxy-polyamides.

High Performance Composites

High performance composites are formed by the incorporation of glass, carbon or Kevlar fibres in matrices of thermosetting polymers such as epoxy resins. For most aerospace applications their attraction lies in their high specific strengths and stiffness, and these characteristics improve at low temperatures but not, perhaps, so markedly as those of metals. One major interest in glass-reinforced plastics for low temperature applications comes, as noted earlier, from their very high strength/thermal conductivity ratios which make them ideal for use as load-bearing, thermally-insulating supports.

As the reinforcing fibres are stronger and stiffer than the matrix, they support the greater part of the applied load and the strength of the composite is determined by the length, orientation, and concentration of the fibres. 50-60 per cent of fibres by volume are typical maximum concentrations unless filament-winding techniques are used. Tensile strengths of 270-420 MPa are typical of room-temperature values and these increase gradually to about 480-700 MPa at 77 K. Their moduli are less temperature dependent, increasing by about 10-20 per cent on cooling from 300 K to 20 K, while their toughness, as measured by impact or notched tensile tests, shows little significant variation over this temperature range. These are quite high strengths by most standards, and when the low density of glass-fibre-reinforced plastics (GRP) is taken into consideration, it can be seen that their specific strengths are extremely high.

Tensile tests carried out on specimens laminated from a single thickness of woven cloth show a change from a high initial modulus to a lower secondary modulus at a load equivalent to about 13-15 per cent of their ultimate load-carrying capacities. If the specimens are examined at this stage they can be seen to be full of microcracks and the material is now porous and unable to retain vapour or liquids. The root of this difficulty lies in the failure of the bond at the fibre-matrix interface in those fibres that have a large stress component resolved perpendicular to the fibres. The strength of this bond is about 12-15 per cent of the composite strength parallel to the fibres. Hence the material has become porous long before it has developed its full potential strength and its electrical properties are also degraded. Fatigue failure also develops by fibre/matrix debonding and resin cracking at stresses lower than those in comparable static tests. Where fatigue loading is expected, design stresses are usually taken as about one-tenth of the composite failure stress.

Glass fibre reinforced composites also have other drawbacks. Static fatigue, which is a characteristic failure mode in bulk glass and unreinforced thermo-plastics, can also occur in GRPs if moisture is able to penetrate the fibre matrix interface, although this failure mechanism does not operate if the composite is maintained at low temperatures. A more serious difficulty lies in the highly anisotropic nature of their mechanical properties, reinforcement being much more efficient in a direction parallel to the fibres than perpendicular to them. Cross-plying the lamination allows two-dimensional reinforcement, but strengths and moduli are reduced compared to those attainable parallel to the fibres. If the orientation of successive plies is varied from layer to layer, this anisotropy can be reduced and more homogeneous properties obtained. This type of laminated structure was utilized in the construction of the NTF fan blades. Two different types of woven E glass cloth pre-impregnated with an epoxy resin were laid up at predetermined orientations and oven cured to consolidate the laminate and fully cure the resin. Other fibreglass structures used in the NTF include pultrusion sections used to fix the foamed glass insulation between the inner aluminium liner and outer stainless steel pressure shell. Further applications of high performance composites will be considered in the next lecture.

7. MATERIAL PROCUREMENT AND QUALITY CONTROL

It should be noted that the construction of cryogenic equipment is subject to the same economic constraints as any other large technical project, in that the total cost of each stage or component needs to be considered when alternative materials are being considered. Thus, to the cost of the basic material needs to be added the cost of the appropriate forming, joining and fabrication processes, inspection and quality control, possible rework and final finishing. It is almost invariably a false economy to purchase material for demanding technical applications at 'rock-bottom' prices as the resultant 'savings' frequently lead to subsequent costly problems, or even rejection of the component. The additional costs incurred in ensuring that a project starts off with top quality material are a worthwhile premium to pay for avoiding the problems likely to arise from the use of poor quality material. It is recommended that the ultimate use of component, and possibly the intended fabrication route should be made known to the materials suppliers when quotations are being sought so that they are aware of the problems that might arise if target specifications are not met. Furthermore, it has often been found that 'misunderstandings' are kept to a minimum if the project engineer makes contact with a technical representative of the suppliers to make him aware of the project requirements, rather than just leaving the purchasing department to progress the order.

8. CONCLUSIONS

In this lecture the author has tried to bring out the philosophy that cryogenic engineering is a mature technology that has much to offer the field of aerodynamic testing through use of the cryogenic wind tunnel. It is, however, important that those without a thorough grounding in cryogenic engineering should make an effort to befifit from accumulated experience on the correct way to handle cryogenic fluids and the best materials to use in the construction of equipment for operation at cryogenic temperatures. To this end, particular emphasis has been laid in this lecture on those aspects of cryogenic engineering that have a direct bearing on safety, in the belief that if potential problems can be understood, it is less likely that actual problems will be encountered. Used with care cryogenic fluids such as liquid nitrogen can bring significant scientific and technical advantages. Misused, the cost could be injury, or even death, of those directly or indirectly involved.

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10. ACKNOWLEDGEMENTS

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MATERIALS AND TECHNIQUES FOR MODEL CONSTRUCTION

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SUMMARY

The problems confronting the designer of models for cryogenic wind tunnel models are discussed with particular reference to the difficulties in obtaining appropriate data on the mechanical and physical properties of candidate materials and their fabrication technologies. The relationship between strength and toughness of alloys is discussed in the context of maximising both and avoiding the problem of dimensional and microstructural instability. All major classes of materials used in model construction are considered in some detail and in the Appendix selected numerical data is given for the most relevant materials. The stepped-specimen programme to investigate stress induced dimensional changes in alloys is discussed in detail together with interpretation of the initial results. The methods used to bond model components are considered with particular reference to the selection of filler alloys and temperature cycles to avoid microstructural degradation and loss of mechanical properties.

1. INTRODUCTION

The advent of large cryogenic wind tunnels such as the National Transonic Facility (NTF) at the NASA Langley Research Center has created many challenges for the designer of models. Optimization of the choice of material and fabrication techniques calls for fine judgment as many of the properties required are near the limits attainable with state-of-the-art technology. Furthermore, in many cases improvements in one direction seem inevitably to be accompanied by losses in others. Thus, for example, the material has to have a yield stress high enough to carry the imposed aerodynamic loadings, yet be tough enough to operate safely at cryogenic temperatures. It has to be capable of being fabricated using available machining and joining techniques to give a model with a precisely known shape and a high quality surface finish which is able to retain dimensional stability during thermal cycling between ambient and its cryogenic operating temperatures. It has to be either intrinsically resistant to, or capable of being protected from, corrosion and degradation and, if it is to be of maximum use as an aerodynamic test facility, it has to be furnished with a complex array of orifices, tubes, sensors, heaters and other components needed for data gathering. While many of these requirements have been familiar to generations of experimental aerodynamicists, it is the high Reynolds number requirement and in particular, the added cryogenic dimension that that has raised the designers' challenge to its present level.

Some idea of the way information on the many factors involved in the design and construction of such models may be generated, stored and transmitted is illustrated schematically in Figure 1. At the conceptual stage the constraints set by the aerodynamic, aeroelastic and instrumentational requirements require the input of data contained in the various locations shown in the "Information Sources" box. Further, more detailed, information is needed at the next stage when a general specification and design study is undertaken. These include materials properties, information on shaping and joining technologies, as well as the cost and availability of candidate materials. When fabrication of a specific model is undertaken, some information on the experience gained should start to flow back via feed-back paths to enhance the cumulative knowledge on both successful and unsuccessful techniques and materials used. Once the model has been put into service, further feed-back should enable its performance and degradation to be monitored. Modifications or the adoption of alternative configurations should also provide valuable opportunities for data feed-back. Finally, once a model has reached the end of its useful life, some form of post-mortem examination would allow comparison of the initial model design requirement with its subsequent performance. Unfortunately much useful knowledge is often lost to the technical community as a whole when pressure of work, or a change of responsibilities, prevents adequate technical documentation of both successful and unsuccessful models.

Many sources of data will need to be tapped to provide the breadth and depth of information required if models for cryogenic wind tunnels are to be fabricated efficiently. Some information on the appropriate cryogenic technology is available in references 1-4 & 22. However, designers often experience considerable difficulty in finding the data they need, partly due the fragmented location of the available information, but also due to the specific nature of the problem. Accordingly, research and development programs have been set up to investigate those areas of technology where information is most urgently needed. Three particular topics being studied at NASA Langley Research Center are: (1) Toughness Enhancement by Grain Refinement, (2) Bonding and Filler Materials and (3) Dimensional Stability and Machining-Induced Deformation in Candidate Materials for Model Fabrication. The author has been closely involved in the latter program and much of the material contained in this paper has been generated or collated under this NASA supported program. Experience generated from other models in conventional as well as cryogenic wind tunnels should be supplemented with that from other relevant technologies. For example, some of the data generated by the requirements of the nuclear fusion power generation program for very large superconducting magnets could have a direct bearing on the cryogenic model program. The rationalization and collation of relevant information from these diverse sources would be of considerable benefit to those involved in the design, fabrication and use of models in cryogenic wind tunnels, particularly if it were to be collated in a " Handbook of Cryogenic Wind Tunnel Model Technology".

In order to reduce unnecessary duplication with the following paper by Dr Young, this paper will concentrate on the the more fundamental aspects of materials and techniques for model construction.

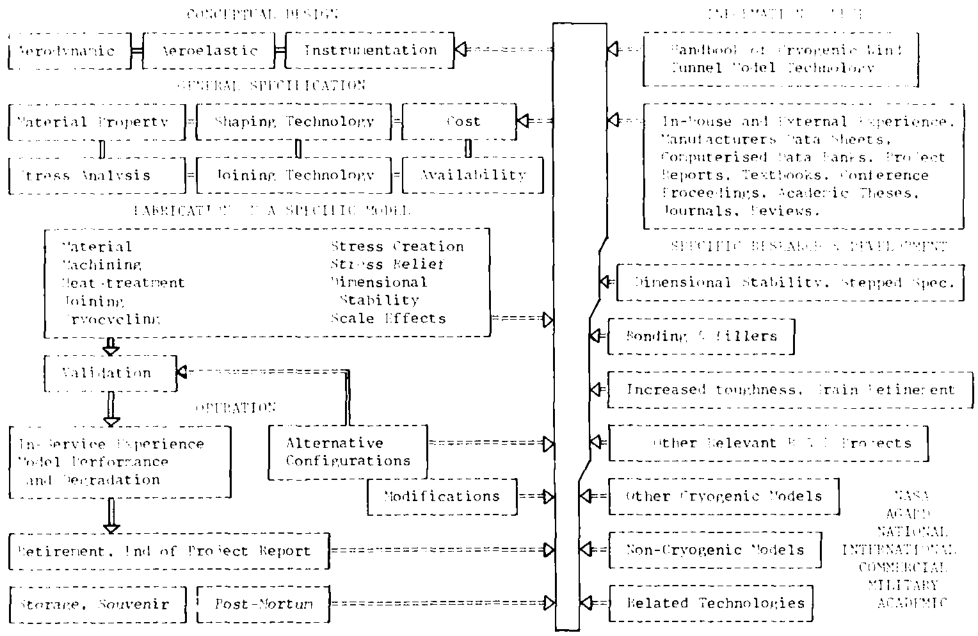


Figure 1. Schematic Representation of Information Transfer and Feedback Paths

2. FUNDAMENTAL CHARACTERISTICS OF METALS

2.1 Relationship between Strength and Toughness

The need for high strength while still retaining adequate toughness for safe operation severely limits the range of alloys that can be considered for the construction of models for large, pressurised cryogenic wind tunnels. The minimum yield stress considered acceptable for Pathfinder 1, the lead model for the NTF, is 1030 MPa, (150 ksi) at 77 K (-320 F). This is not, in fact, a high stress level and the fracture toughness requirement of at least 93.5 MPa $\sqrt{m}$ (85 ksi $\sqrt{in}$), or a Charpy V notch Impact Energy of 34 J (25 ft-lbs) is not excessively cautious. However, applied together these two design requirements combine to narrow drastically the range of candidate materials. Basically, this is because most metallurgical techniques that increase the yield stress also bring about a decrease in fracture toughness. Furthermore, as the critical flaw size in a structure is related to the crack size factor, $(K_{Ic}/\sigma_y)^2$, an increase in yield stress without a corresponding increase in fracture toughness will lower the resistance of the material to unstable, low-energy crack propagation. This toughness-versus-strength trend for structural materials is well illustrated in Figure 2, as modified by Rush (Ref. 31) from Toblers original (Ref. 22). Most materials fall between the two trend lines, those at the upper boundary having the highest toughness for a given yield stress. It should, however, be noted that these optimum properties are often not shown in the particular product form delivered for model fabrication. Considerable effort is under way to produce materials having properties which lie above the upper trend-line of Fig. 2, and there are two different basic approaches to this objective:

- Increasing Strength without Loss of Fracture Toughness as in the high nitrogen and high manganese stainless steels.

- Increasing Fracture Toughness without Loss of Strength in ferritic steels by the use of multiple stage heat-treatments through the austenite /austenite + ferrite phase transformation region.

Significant toughness improvements have been achieved by Rush (Ref. 19) in 9% Nickel, HP 9-4-20 and 18Ni 200 maraging steel using this second approach.

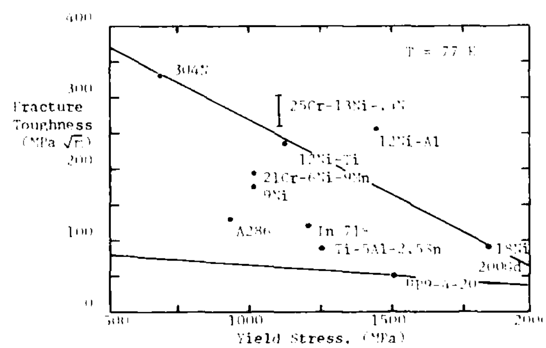


Figure 2. Toughness-vs-Strength Relationship

2.[illegible] Dimensional Stability

In order to meet the minimum acceptable toughness requirements a number of precipitation-hardened stainless steels have to be heat treated to a lower strength condition and it has been found that this can lead to dimensional instability. There are two basic mechanisms that can cause such instability:

- metallurgical structural instability in which one phase transforms partially or fully into a second phase which has a different crystal structure and volume.
- deformation due to the creation, or relief, of unbalanced induced or residual stresses.

Stress-induced dimensional changes will be considered further in section [illegible]. The occurrence of severe dimensional instability in a model first came to light in [illegible] airfoil made from 15-5PH stainless steel and tested in the [illegible] Transonic Cryogenic Tunnel at NASA LaRC. A post-testing co-ordinate check [illegible] in. [illegible] of the aft airfoil section ([illegible] in. chord) and a [illegible] in. bow over an [illegible] in. [illegible] investigation showed that the material had been heat-treated to the H1150M condition in order to achieve a Charpy impact energy in excess of the required minimum of 25 ft-lb. Table 1 shows manufacturers data on the relationship between condition, impact energy, tensile strength and contraction during the heat-treatment cycle, to which we have added comments on the structure and cryocycle stability. It can be seen that relatively little contraction is associated with the H900, H1025 and H1100 heat-treatments as these do not alter the martensitic structure of the material. The H1150M heat-treatment is accompanied by a much larger contraction as some martensite is transformed to austenite and it is the presence of this austenite that gives the material its improved toughness and impact energy. This austenite is, however, only metastable and low temperature cycling, machining or other forms of deformation trigger off a partial transformation back to martensite which is accompanied by a volume expansion. In an asymmetric section such as an airfoil, and where the effect of machining would be more pronounced in thinner sections than in the thicker parts, the volume changes show up as warpage. (Ref. [illegible]).

Table 1: 15-5PH Stainless Steel Stability Data (Ref. [illegible])

Condition	77 K Charpy Impact ([illegible])	Contraction (R.T.-H.Temp.) (%)	Cryocycle Stability	300 K [illegible] (MPa)	Structure
[illegible]	[illegible]	[illegible]	-	1310	martensitic
[illegible]	[illegible]	[illegible]	good	[illegible]	m/s
[illegible]	[illegible]	[illegible]	-	[illegible]	m/s
[illegible]		[illegible]	-	[illegible]	m/s + aust.
[illegible]	[illegible]	[illegible]	poor	793	m/s + aust.

The energy required to trigger off the austenite to martensite transformation (an instantaneous [illegible] nucleation and diffusion-controlled growth mechanism) is probably provided by differential [illegible] during thermal cycling. Large temperature gradients would encourage such transformation, as [illegible] temperature changes, and thus is is the rate of cooling and warming and the number of cryogenic cycles that determine the degree of transformation, rather than the length of time held at a particular temperature. [illegible] changes of section would also exaggerate the problem as larger temperature gradients, and hence higher thermal stresses, are set up across thicker sections. In the case of the 15-5PH airfoil the dimensional changes continued over many tens of thermal cycles, the incremental change becoming gradually smaller as the amount of metastable austenite transforming decreased. As, however, the toughness decreased progressively in step with the austenite transformation, there was no point in continuing to cycle the model to achieve dimensional stability as its toughness would then become unacceptably low. In other, more stable, materials where some dimensional instability has been created by machining-induced stresses, it is possible to achieve effective metallurgical and dimensional stability be carrying out a few cryocycles prior to finish machining, providing that significant stresses are not re-introduced at this stage.

3. REVIEW OF ALLOYS USED FOR MODEL CONSTRUCTION

3.1 Austenitic Stainless Steels

3.1.1 AISI 300 series

The face-centered-cubic structure of the AISI 300 series stainless steels is rendered more or less stable at and below room temperature by the presence of austenite stabilizers such as nickel, manganese, carbon and nitrogen. The 20% nickel present in type 310 makes it particularly stable, but it has the lowest yield strength of the 300 series. In the leaner grades, particularly the readily available 304 and 304L grades, the total concentration of austenite stabilizing elements may not be high enough to prevent some transformation to martensite, with its consequent volume change. This change can be induced thermally by lowering the temperature below the Ms (martensite start) temperature, or by mechanical deformation at temperatures below the Md (martensite deformation) temperature, which is usually a few hundred degrees higher than the Ms. These temperatures may be calculated from equations given in Ref. 1[illegible] if the composition of the alloy is known. However, it is only the high-nitrogen versions of the 300 series that are likely to be strong enough for use for cryogenic models and these are some of the most stable members of the series. Of particular interest are alloys such as that developed for the Japanese Atomic Energy Research Institute (JAERI) fusion reactor program which set a target of 1200 MPa for the 4 K yield strength, together with a 4 K Charpy impact energy of 100 J. A 25Cr-13Ni-.4N alloy, SUS 170, developed by Nippon Steel (Ref. 20) has achieved this 4 K goal and its 77 K yield strength of 1130 MPa and a Charpy V energy of [illegible] J make it highly attractive for highly stressed cryogenic wind tunnel models.

One feature common to almost all of the austenitic stainless steels is their ability to become sensitized if they are held for a significant time in the temperature range between 590 and 920 C (1100-1700 F). This is due to the precipitation of carbides and sigma phase at the grain boundaries and it has two particularly deleterious effects on the material. At room temperature the main effect is to cause "weld-decay", a liability to inter-granular corrosion brought about by the loss of chromium adjacent to the grain boundaries. Of more significance for cryogenic applications is, however, the serious loss of toughness at liquid nitrogen temperatures due to the ease with which fracture can be nucleated and

trapped in a low energy mode in the precipitate laden grain boundaries. Unfortunately, airfoil models are frequently cooled through this sensitizing temperature range after post-machining, stress-relieving heat-treatments at [illegible] or during brazing. Should sensitization occur it can be removed by reheating to [illegible] and then cooling rapidly through the sensitizing temperature range. This is, however, difficult to achieve with large, thick sections in a vacuum oven. One common method of preventing sensitization is to specify one of the "weld stabilized" grades such as the titanium bearing AISI 321 or the niobium bearing type 347. These additional elements are strong carbide-formers and they react with any free carbon to prevent chromium depletion. An alternative approach favoured for room-temperature applications is to specify a low-carbon grade such as 304L or 316L, but as carbon is an austenite stabilizer these alloys are less stable at cryogenic temperatures. It is also worth noting that type 316 has a better corrosion-resistance, especially in marine atmospheres, due to its 2-3% molybdenum content.

3.1.2 Fe-Cr-Ni-Mn-N Alloys

Strengths higher than those of the 300 series can be obtained from these steels as their increased manganese content raises the nitrogen solubility limit. One particular material in this series, Nitronic 40, a 21Cr-6Ni-9Mn-0.4N alloy, was chosen for the construction of the Pathfinder I Model for the NTF and a 2 dimensional airfoil manufactured by McDonell-Douglas for the NASA LaRC 0.3m TCT. Some problems were encountered due to grain boundary sensitization created during fabrication, but in the 2D airfoil these were removed by heating to 1000 C and then quenching into liquid nitrogen to achieve a controlled and uniform cooling rate. Although the material was supposed to be 100% austenitic it was found to contain up to a few % delta ferrite, a body-centered-cubic phase of lower toughness than the parent metal. Remedial heat treatments were unable to remove this stable delta ferrite and caused unacceptable grain growth (Ref. [illegible]). However, fracture toughness tests gave very high values at 77 K and, as the delta ferrite was aligned along the rolling axis and the span of the model wing was also in this direction, it was felt that the fracture toughness would be adequate to ensure safe operation in the NTF. Nitronic 40 can be machined using conventional techniques but care has to be taken to ensure good cooling as the material work hardens easily and tools can rapidly loose their cutting edge. Availability of the material in the form of bars and plates of the required size can also be a problem which seems to be getting more severe.

Other high manganese-high nitrogen alloys such as Nitronic 33 (18Cr-3Ni-13Mn-.27/.40), Nitronic [illegible] ([illegible]Cr-[illegible]Ni-[illegible]Mn-.27/.45) and Carpenter 18-18 plus (18Cr-18Mn-1Mo-1Cu-1Si-0.5N) are generally considered to have toughnesses too low for safe cryogenic operation. In the AISI 200 series of steels the high-manganese contents are used primarily to increase nitrogen solubility and hence strength. The earlier alloys had poor fracture toughness at cryogenic temperatures, but more recently a modified AISI 205 steel, nominal composition [illegible]Mn-[illegible]Ni-[illegible]Cr-0.02C-0.22N, has been shown by Ogawa and Morris (Ref. 17) to give yield strengths of [illegible] Mpa and Charpy impact energies of [illegible] J in the as-rolled condition at 77 K. However, these alloys are not yet easy to obtain, particularly in the product forms likely to be needed for model construction.

3.1.3 A286

This precipitation hardened stainless steel has become one of the state-of-the-art materials for the construction of models for cryogenic wind tunnels and it has been used for a variety of 2 and 3 D models in the NASA LaRC 0.3-m TCT with considerable success. A286 screws are frequently used to fasten together smaller components and in the following paper Dr. Young will discuss NASA LaRC experience with their use and the various locking systems that have been evaluated to prevent them from unscrewing under aerodynamic loading or cryogenic temperature cycling. The alloy was not considered strong enough for use in Pathfinder I as its yield stress at 77 K is only about [illegible] MPa, but more recently it has been used for the fabrication of a model of the space shuttle to be tested in the NTF. Its nominal composition is: Fe-[illegible]Ni-[illegible]Cr-2.2Ti-1.3Mn-1.2Mo-0.3V-0.2Al--0.5Si and it is the titanium, vanadium and aluminium additions that precipitation harden the material during heat-treatment. The material is fully stable with respect to martensitic transformation both during cryocycling and deformation at cryogenic temperatures. Machining is rather difficult due to the tendency of the material to work-harden rapidly and tool wear can be excessive. Furthermore the studies of stress-induced dimensional changes to be discussed in section [illegible] have shown that large surface stresses are produced even during rough machining. It is a relatively expensive material and there are also often difficulties in obtaining it in the desired [illegible] partially [illegible] the considerable use of the material for strategic, high-temperature [illegible].

3.2 Martensitic and Semi-Austenitic Stainless Steels

3.2.1 AISI 600 Series

Among this class of material are a number of materials [illegible] successful histories in the fabrication of models for use in ambient and high temperature [illegible] due to their ease of fabrication and ability to hold a high quality surface finish. [illegible] the materials were used in the fully-hardened condition but it was recognized that [illegible] condition they would be too brittle for cryogenic applications. The RH1050 heat-treatment was therefore used to bring the Charpy impact energy up to the required minimum of 25ft-lb, but, as noted earlier, this caused dimensional instability in a 15-5PH airfoil when the metastable austenite re-transformed to martensite during cryocycling. Similar problems have been found, or can reasonably be expected, to occur with 17-4PH, 17-7PH, Custom 450, AM 350, AM355, PH15-7Mo and PH14-8Mo and these materials are not recommended for cryogenic use.

3.2.2 PH14-8Mo

The picture is, however, slightly different for PH13-8Mo. From a comparison of the contraction rates that occur during the various heat-treatments shown in Table 2 (Ref. [illegible]) for PH13-8Mo with those previously given for 15-5PH in Table 1, it is clear that austenite is reformed during the higher temperature heat treatments. It would, however, appear that this austenite is more stable than that formed in the other alloys in this series. Berry and Jasper (Ref. 11) comment as follows:

"(After) heat-treatment at the lowest ageing temperature, in this case [illegible], the microstructure is essentially completely martensitic. As the aging temperature increases, so does the

amount of reformed austenite. The H1150M condition (the softest for these steels) has a rather complex microstructure. Heating to 760 C (1400 F) results in much of the martensite going into solution at that temperature. Upon cooling to room temperature, some of the austenite is transformed into untempered martensite. The rest of the austenite remains as austenite and the balance is highly overaged martensite. The 620 C (1150 F) ageing then ages the martensite that was formed as a result of cooling from 760 C (1400 F), together with some additional reformed austenite. Therefore, the final microstructure consists of highly overaged martensite, normal overaged martensite and reformed martensite which is completely thermally stable (authors underlining). This results in a heat-treated stainless steel with reasonably *good impact strength* at temperatures as low as 77 K (-320 F)."

Table 2: PH13-8Mo Stainless Steel Stability Data (Ref. 11)

Condition	77 K Charpy V Impact J (J)	Contraction H.T.-R.Temp. (%)	Cryocycle Stability	300 K UTS (MPa)	Structure
H950	2.7	0.04-.06	-	1551	martensitic
H1000	5.4	0.04-.06	-	1462	m/s
H1050	5.4	0.05-.08	good	1310	m/s
H1100	6.8	0.08-.12	-	1103	m/s
H1150	-	0.30	-	1000	m/s + aust.
H1150M	41	0.35	reasonable	896	m/s + aust.

In the H1150M condition PH13-8Mo has a yield strength of 1000 MPa at 77 K and Charpy V impact energies between 40-80 J (30-60 ft-lb) depending on the source of the data. It is therefore comparable to Nitronic 40 in its properties and its structure has been considered in so much detail because it has been used for the construction of the solid wing for Pathfinder 1 and the half-scale Pathfinder 1 model. Nevertheless there have been indications that, although the "complete thermal stability" referred to above may be true in the context of conventional applications, the very high dimensional stability demanded of models for cryogenic wind tunnels *might not* be met by PH13-8Mo in the H1150M condition. It was possible that deformation induced during machining might trigger off further transformation of austenite to martensite that could, in turn, create dimensional instability on cycling to cryogenic temperatures. The material was, therefore one of the first studied in the stepped specimen program to be described in section 4. Some evidence was, indeed, found for dimensional changes after 3 cryocycles into liquid nitrogen, but no further movement occurred as a result of further cryocycles, suggesting that the structure of the material had stabilized during the initial cryocycles. Experience *with the two model parts made* for the NTF gives further confidence for the continued use of PH13-8Mo for cryogenic models, as both proved to be completely stable. Both had been thermally cycled to liquid nitrogen temperature at the semi-finished machining stage to allow transformation of any unstable austenite and it would appear that final finishing did not further destabilize the structure. (Refs. 27 & 28).

3.3 18 Nickel Maraging Steels

Although they do not have the favoured austenitic structure, this family of high-strength steels are strengthened by precipitation hardening of the soft, low-carbon martensite to form a stable microstructure which is not adversely affected by thermal cycling to cryogenic temperatures. Furthermore they are readily machined in the annealed condition and there is very little dimensional change during the single step ageing heat-treatment which takes place at the relatively low temperature of 480 C (900 F). The higher strength members of the family have unacceptably low toughnesses for most cryogenic applications, but the lower strength 200 and 250 grades, are tough enough to find application in many high load-bearing applications in cryogenic wind tunnels. For example, the 250 grade is used for the construction of stings, while the 200 grade is the most widely used material for constructing models for the NTF. At least eight models, or substantial parts thereof, have been constructed or are still under fabrication at present. The 200 grade has a nominal composition (Fe,-17 / 19 Ni,-3 / 5.2 Co,-0.15 / 2.0 Ti,-0.05 / 0.2 Al,- 0.03 C,- 0.10 Mn,- 0.01P). *Its yield strength* is 1860 MPa at 77 K and it has a Charpy V notch impact strength in the region of 25-50 J (18-37 ft-lb) depending on the product form. The increasing difficulty of obtaining reliable supplies of cobalt have let the major US supplier of 18 Nickel maraging steel to introduce a series of cobalt-free alloys and the 200 grade is currently under active evaluation for possible use in the fabrication of cryogenic wind tunnel models. (Ref. 10).

As noted earlier the low-temperature toughness, as indicated by the Charpy V notch impact energy at 77 K can fall below the 25 ft-lb minimum required for NTF operation in some product forms. The grain-refinement program referred to in section 2.1 has shown that significant increases can be obtained in the toughness at 77 K. The grain-refining process consists of multiple heating and cooling cycles between the austenite and the dual-phase austenite + ferrite region, followed by rapid cooling to reduce the grain size.

3.4 Ferritic, Quenched and Tempered, and Grain-Refined Steels

In lecture 2, it was noted that the 9 Nickel steels are the only ferritic alloys considered suitable for use at 77 K and the main drive shaft for the NTF fan is made from a special grade of this alloy. The material has also been considered for use in model construction, but the more recently developed 12 Nickel alloy looks more promising. Furthermore, as both 9% and 12%Ni steels undergo a ferrite *to austenite phase change* they are therefore capable of grain-refinement by multi-stage heat-treatment.

3.4.1 9 Nickel Steels

Two grades of 9 Nickel steel are readily available: the double normalized and tempered A 353 and the quenched and tempered A 553 which has a slightly better toughness and about a 10% higher strength than the double normalized grade. Both grades are relatively easy to obtain, readily machined and welded, but there is no matching filler and austenitic nickel-based fillers have to be employed to give adequate strength. Unfortunately, this leads to a miss-match in the expansion coefficients and potential *problems*

with thermal fatigue and stability. Furthermore, the 9 Nickel steels are not very corrosion resistant and suitable coatings would need to be applied to protect the surface of a model.

3.4.2 12 Nickel Steels

Initial work by Stephens and Witzke (Ref. 21) at NASA Lewis Research Center has recently been extended by Rush (Ref. 31) at NASA Langley Research Center. Two alloy compositions, Fe-12 Ni-0.5 Al and Fe-12 Ni-0.25 Ti, have been selected for further development and this will be discussed in detail by Dr. Young. Suffice it to say that, if the results of the experimental heats are reproduced in the larger production melts, these alloys appear to offer considerable potential for use in cryogenic models. The initial data on strength and toughness of both alloys at 77 K has been included in Fig. 2 and it can be seen than the 12 Ni-Al alloy in particular has a combination of strength and toughness which places it above the upper trend line for current materials.

3.4.3 Quenched and Tempered Steels

The quenched and tempered 9Ni-4Co steels, particularly HP 9-4-20, have been used for 2 Dimensional models with some success. They have also been included in the grain refinement program and significant improvement in toughness at 77 K has been achieved. However, there are reservations about its dimensional stability and its relatively poor corrosion resistance limits its potential usefulness.

3.5 Aluminium Alloys

Aluminium alloys may be divided into two groups according to their basic metallurgical strengthening mechanisms: [1] the solution-hardened alloys which are very ductile but only of moderate strength unless cold-worked, and [2] the stronger, heat-treatable, precipitation-hardened alloys. Type 5083 is probably the most widely used of the solution hardened alloys, due in part to its excellent weldability. Even in the as-welded condition its full strength is retained, thus giving it an advantage over the nominally stronger heat-treatable alloys if post-weld heat-treatment is not possible. For example, alloy 6061 in the solution-treated-and-artificially aged T6 condition is stronger than that of 5083, but as-welded its strength drops below that of as-welded 5083. A series of six solids of revolution having the same size and shape as model bodies to be tested in the NTF have been made out of alloy 6061 in the T6 condition. Of the other heat-treatable alloys, the aluminium-copper 2014 and 2219 have been used in a number of aerospace cryogenic applications where their high strength to weight ratio is advantageous. The toughness of the very high strength 7000 series alloys is, however, too low for most cryogenic purposes.

A number of cryogenic wind tunnel models, or parts thereof, have been built from aluminium alloys and operated successfully. However, their elastic modulii and strengths are generally too low for their use in the more heavily-loaded components such as airfoils in pressurised tunnels such as the NTF. Complications can also arise when aluminium and steel components are mixed in the same model, as the two materials have significantly different coefficients of thermal expansion. Nevertheless, aluminium alloys are easy to machine and readily weldable, although brazing and soldering are not easily carried out in model fabrication. The surfaces of models also need some form of protection to prevent them from being scratched.

3.6 Titanium Alloys

Two titanium alloy have been used for cryogenic components, particularly in aerospace applications where their high strength to weight ratio is a distinct advantage. The Ti-5Al-2.5Sn alloy has a stable h.c.p. structure and can be used down to 77 K, whereas the Ti-6Al-4V alloy has a duplex h.c.p. / B.c.c. structure and is not used below 77 K because of excessive notch brittleness. For cryogenic use the special ELI (Extra Low Interstitial) grades have to be specified because the toughness of titanium is severely degraded by too many interstitial elements. As these include carbon, nitrogen, oxygen and hydrogen, great care has to be taken during fabrication, particularly welding, to prevent their pick-up. Furthermore, titanium alloys are not easy to machine, they are relatively expensive and for these reasons few, if any, models for cryogenic wind tunnels have yet been made in titanium alloys.

3.7 Nickel Based Alloys

All nickel-based alloys have the austenitic structure that makes them suitable for cryogenic applications, but relatively few have, as yet, been used for model construction. This is most probably due to a combination of their relatively high cost, poor availability and the considerable difficulties experiences in machining the high strength alloys such as the Inconels using conventional machining techniques. However, advances in chemical milling, electrical discharge machining, electron beam welding and other modern technologies have reopened the question of their possible application for model building. Nickel coatings have been used to rework model surfaces that have been undercut during machining or damaged in service, electroless nickel being used where hard finishes are required while electrolytic nickel is preferred if high ductility is needed. Nickel-copper alloys, Monels, have excellent corrosion resistance and have been used for cryogenic applications, but they do not posses any outstanding advantages that make them attractive for model building. The most promising alloys are the nickel-chromium Inconels, in particular the precipitation-hardened types 718 and X750. Inconel 718 has the higher yield strength, 1172 MPa at 300 K and 1342 MPa at 77 K, while X750 has a slightly lower strength but higher toughness.

3.8 Copper Based Alloys

Copper based alloys have limited applications for cryogenic models and are used in those applications that make use of their good thermal and electrical conductivities, their availability, or the ease with which components can be machined and joined. Commercially pure copper is used for electrical conductors and is readily available. Copper-zinc alloys, such as the 70Cu-30Zn alpha brasses and the bronzes, particularly phosphor, silicon and aluminium bronzes, tend to be used for small, lightly-loaded components that are easily machined from available product forms. Brasses are readily soldered or brazed,

although the temperatures involved in most brazing operations would anneal any cold-worked material. It is, however, the precipitation-hardened beryllium coppers that are possibly of most interest for model construction. The relatively small amount of beryllium needed to form the precipitates that allow the room temperature yield strengths to reach 1000 MPa in the fully-hardened condition do not excessively degrade the high thermal conductivity of pure copper. Beryllium copper is particularly useful in those circumstances where good thermal conductivity is needed to minimize cool-down time or temperature gradients and it is often used to form high-conductivity inserts to take heat away from particularly critical regions. The main drawback of the material lies in its very low toughness at cryogenic temperatures in the fully hardened condition. Nevertheless a 2 % beryllium copper airfoil has been made by the Douglas Company and tested successfully in the 0.3-m TCT at NASA LARC. (Ref. 13)

4. STRESS-INDUCED DIMENSIONAL CHANGES IN METALLIC ALLOYS

4.1 Induced Stresses and their Effect on Dimensional Stability

Stress-induced deformation can produce dimensional changes of many thousandths of an inch on typical airfoil model sections. These stress systems can be of considerable magnitude and can originate from one or more of the following mechanisms:

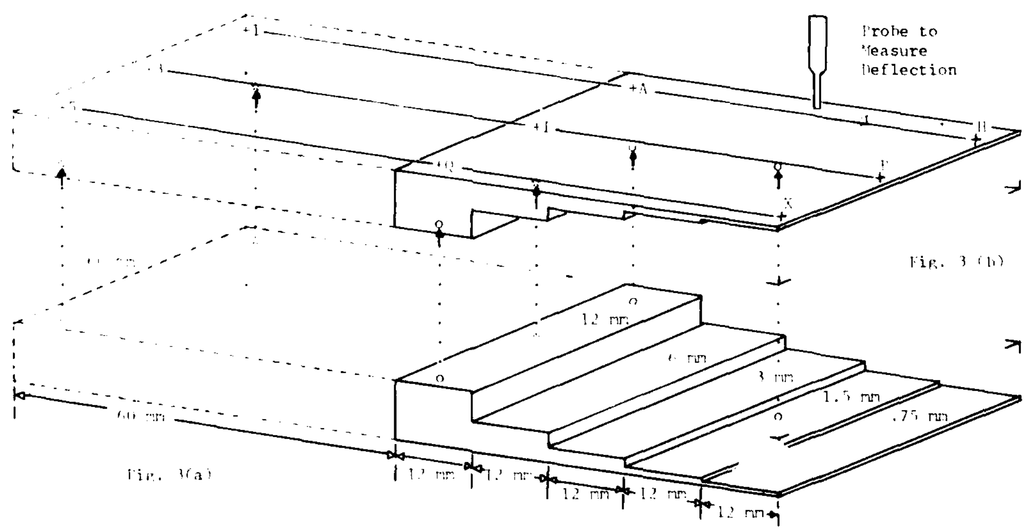
- unbalanced residual compressive and tensile stresses set-up during the original fabrication.
- quench-induced stresses generated on cooling from high temperature heat-treatments.
- compressive or tensile surface stresses induced by machining. These can be elastic or plastic depending on the degree of deformation created during mechanical working of the material and they can cause phase transformations in the surface layers.
- stresses created by temperature gradients, particularly across uneven sections.

Many different configurations were used in the initial investigations, including fully profiled airfoils and wedge shaped specimens with thin, tapered trailing edges representative of typical airfoil models. However, in view of the large number of possible combinations of material, machining technique, heat-treatment and other fabrication processes, a simplified, yet representative, stepped specimen configuration was adopted by NASA LaRC to allow these effects to be identified separated and quantified.

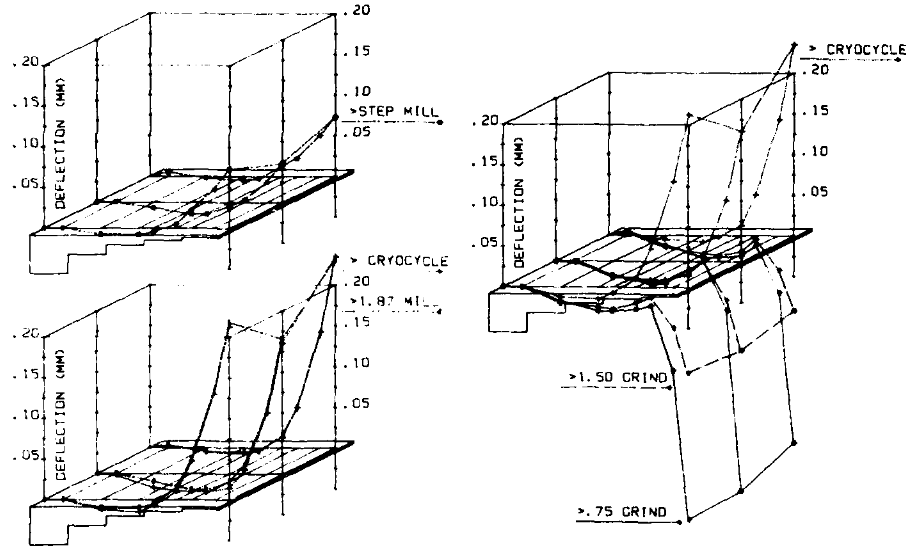
4.2 The Stepped Specimen Program

4.1.1. Specimen Configuration

The configuration used for the first 18 specimens of 18Ni 200 grade maraging steel, A286 and PH13-8 Mo stainless steel is illustrated in Fig 3(a). (Ref. 26) By limiting the maximum thickness to 12 mm, it was possible to fabricate specimens from readily available 1/2 inch plate and the choice of 60 mm width and 60 mm length minimized the amount of material required. In its final form the specimen has five steps of length 12 mm and thickness 12, 6, 3, 1.5 and 0.75 mm, the thinnest giving the most sensitive region for observing the effects of fine finishing cuts. The flat underside of the specimen provides a firm support for machining operations carried out on the top surface. It also acted as the reference surface for subsequent validation measurements when the specimens were inverted and supported at the three points marked with o symbols in Fig. 3(a). However, interpretation of the deflections of the reference surface were complicated by the fact that the 3rd support point lay within the machined region. For the latest series of specimens the configuration was, therefore, modified to increase the length to 120 mm, as indicated by the dashed lines in Fig. 3 (b), and allow the three support points marked with * symbols to be contained within the unmachined region. (Ref. 28)



Figures 3(a) and (b). Configurations of Original and Modified Stepped Specimens



Figures 4 (a), top left, (b), bottom left, and (c), right. Machining-Induced Deformation in A286

4.1.2. Initial Results and their Interpretation

Many different operations were carried out sequentially on each specimen in order to gather as much information as rapidly as possible. Milling with ball-ended cutters was used to reproduce the type of stresses induced during initial shaping on multi-axis CNC machines, with grinding used to represent the finishing stages. Feed rates, thickness of each cut and other machining details for each material were specified to be as used in actual model fabrication. For the proof-of-concept specimen made from 18 nickel 200 grade maraging steel, continuous measurements of the machining-induced deflection were made along the three lines A-H, I-P and Q-X shown in Fig. 3 (b). After milling the reference surface was found to have an upward deflection, indicating that compressive stresses were created by milling the opposite face. By treating the specimen as a cantilevered beam, it was possible to calculate the magnitude of these compressive surface stresses. These were found to increase from 36 to 62 MPa. (5 to 9 ksi) over the 4 milling cuts, each of depth 375 microns (0.015 in.), used to reduce the thickness from 3 to 1.5 mm. Subsequently, 17 similar specimens of A286, PH13-8Mo and 200 grade maraging steel were put through a similar machining sequence. Eight readings were taken along each of the three lines A-H, I-P and Q-X to give a total of 24 data points. (Ref. 27).

The effect of of the different machining operations was followed by joining these points to reconstruct the appropriate reference surfaces as shown in Fig 4 (a) to (c) for an A286 specimen. The surfaces shown are: (a) after milling the 6 and 3 mm steps, (b) after milling the 1.5 mm step and after cryocycling, (c) after cryocycling, after grinding the 1.00 mm step and after grinding the 0.75 mm step. The reproducibility of the shape of the surfaces before and after cryocycling in Fig. 4 (b) is an impressive confirmation of the excellent dimensional stability of A286 at cryogenic temperatures.

4.1.3. Subsequent use of the Modified Specimen Configuration

The dip in the reference surfaces below the original reference plane in Figs. 4 is a consequence of the location of the third support point in the machined area of the specimen. As noted earlier the modified specimen configuration avoided this problem and allowed easier interpretation of the surface deflections. Improvement in the measuring technique also allowed over 360 data points to be gathered along each of the three lines 1 to H, 3 to P and 5 to X, thus effectively creating continuous traces. This increased precision allowed dimensional stability during cryocycling to be studied in more detail. Fig 5 shows how a specimen of PH13-8Mo moves during initial cryocycling, but then remains completely stable during subsequent cryocycles. This characteristic is exploited in practice by cryocycling models before finish machining to allow any necessary relaxation or phase transformation to take place before the model enters service. (Ref. 28)

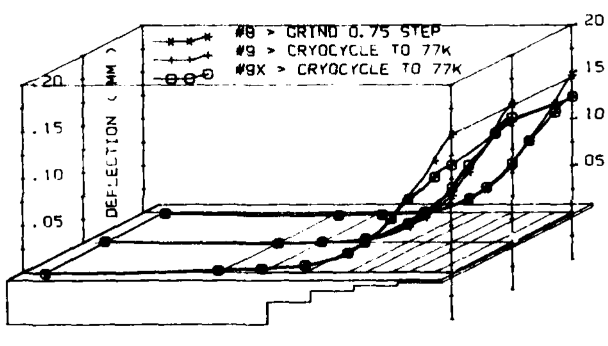


Figure 5. Machining-Induced Deformation in a PH 13-8Mo Specimen with the Modified Configuration.

The very large deflections displayed after machining the thicker steps indicate that large surface stresses are created by work-hardening during milling and grinding, a confirmation of workshop experience that the material is difficult to machine. The common practice of machining opposite faces alternately does, however, tend to balance the surface stresses created on each side and thus prevent such large deflections occurring on an actual model. The shapes of the surfaces in Fig. 4 indicate that grinding sets up tensile surface stresses, as the sign of the deflections created during milling was reversed by grinding.

It would, therefore, appear that if warpage occurs during rough machining of, for example, a 2 or 3 D airfoil, and if at least one surface is still over-size, dimensional fidelity could be restored by milling or grinding that surface to induce an appropriate balancing compressive or tensile surface stress.

4.1.6. Future Program

It is envisaged that the next phase of the program will involve further in depth study of the materials most likely to be used for the fabrication of cryogenic wind tunnel models, particularly the 200 grade maraging steels. Separate specimens will be used to measure the stresses created in different machining operations such as milling, grinding, lapping and hand finishing, as well as the supposedly stress-free techniques such as EDM and chemical milling. Stress-relieving heat-treatment cycles will also be investigated to determine their ability to remove machining-induced deformation. Scale effects will be studied using larger sized specimens, and stress-balancing investigated by developing techniques of validating specimens machined on both sides. (Ref. 29).

5. JOINING TECHNIQUES FOR METALS

Attainment of the optimum mechanical properties of materials at cryogenic temperatures requires careful control of their microstructure. In particular, the desirable combination of high strength and adequate toughness is only attainable if the grain size can be kept small and the grain boundaries free from degradation by sensitisation. Any joining technique that involves heat input must be evaluated carefully to ensure that neither the grains nor their boundaries are degraded during, or subsequent to, the joining process.

During conventional fusion welding enough heat has to be input to cause localised melting of the parent metal and this also causes annealing and modification of the adjacent heat-affected zone. For almost all wind tunnel models, the heat inputs from welding processes such as MIG, TIG, MAG, etc. are too great and the resultant heat-affected zones too large for these processes to be acceptable. However, in the case of electron beam and laser welding, heat inputs are so low and control of the heat-affected zone so good that these techniques are becoming indispensable for joining together sub components. For example, many airfoils are designed with cover plates that allow access to the centre of the airfoil for the passage of pressure tubing from the sensing orifices on the airfoil surface. Electron beam welding has been used on many airfoils to secure fully profiled coverplates to the rest of the airfoil without damaging the tubes or their joints. It is reported by Griffin (Ref. 14) that laser welding without the use of fillers can produce strengths equal to that of the parent metal after heat-treatment. The region affected is limited to a diameter of about 0.62 mm (.025in) and a depth of between 0.5 and 1.2 mm (.02 to .05 in) and is thus particularly useful for joining thin sections.

Austenitic stainless steels such as the precipitation hardenable A286 and Nitronic 40 (21Cr-6Ni-9Mn-0.3N) can be brazed using nickel-based fillers such as the Ni-7Cr-3Fe-4.5Si-3.2B alloy (AWS4777), BNi2 to give ductile joints with strengths similar to the parent metal yield strength. These alloys, which are brazed at temperatures in the range 1010-1175 C (1850-2150 F), are of particular interest as they contain melting-point depressants such as boron and silicon which diffuse from the molten filler metal into the parent metal and cause the filler to solidify isothermally as the boron and silicon concentration drops. They have been used successfully in a research program to develop a fabrication technique for the construction of 2 and 3 D airfoils by bonding together two or more flat plates containing pre-machined channels that subsequently become pressure passages in the bonded airfoil. Small samples have been produced without blocked channels or cross-leaks between them and current developments are concentrating on scaling up towards airfoils large enough for use in one or other of the NASA LaRC cryogenic tunnels. For optimum bonds the gap between the two surfaces to be bonded, the faying surfaces, should be of the order of 0.025 to 0.05 mm (.001 to .002 in) and such dimensions are easy to maintain in small samples. However, as warpage out of the plane of the plates tends to increase as the square of the plate diameter, this becomes increasingly more difficult in larger samples. A better understanding of the factors controlling dimensional stability, hopefully to be obtained as a result of the stepped specimen work described earlier, will be necessary before this technique can be used routinely for airfoil fabrication.

During brazing enough heat has to be supplied to the components to allow the filler metal to flow, wet the faying surfaces and fill the gaps between them. In general, the highest strength fillers melt at the highest temperatures and there is the greatest risk of causing grain growth when they are used. It has already been noted that a special heat-treatment has been developed to reduce the grain size and thus improve the otherwise marginal cryogenic toughness of the 18 nickel 200 grade maraging steels intended for fabrication of models for the NTF. However, most of these models needed brazing and, as serious grain growth starts at temperatures above about 1000 C (1830 F) in these maraging steels, the AWS4777 type of fillers cannot therefore be utilised. Good results were, however, obtained in an experimental program using a newly developed 47Ni-47Pd-6Si alloy (Metglas MBF-1005X) and brazing temperatures in the range 900-965 C [1650-1770 F] (Ref. 31). Other maraging steel models have been brazed using the more established silver-copper alloys such as AWS BAG 3 (50Ag-15.5Cu-15.5Zn-16Cd-3Ni) which can be brazed at temperatures between 780 and 900 C (1435 to 1650 F). As the recommended solution annealing temperature for these maraging steels is about 815 C (1500 F), the two operations could be combined if so desired. Ageing takes place at between 315 and 705 C (600 to 1300 F) and it has been suggested (Ref. 14) that brazing and ageing could be combined in the same heat-treatment using an aluminium filler to produce a diffusion brazed bond. However, initial experiments at 480 C (900 F) using pressures of 28 MPa (4 ksi) failed to produce consistent bonds with adequate strengths. The instrumented wing of Pathfinder 1, which was fabricated in Nitronic 40 (21Cr-6Ni-9Mn-N) stainless steel, was brazed using an 82% Au - 18% Ni alloy melting at 955 C (1750 F).

The temperatures involved in brazing operations are often high enough to give partial or complete relief of residual stresses created during previous machining operations and, if these stresses are unevenly distributed, distortion can occur. In extreme cases cracks have been found to propagate during brazing, or subsequent cooling and the choice of heating and cooling temperature profiles is often difficult. Ideally, rapid cooling is advisable through temperature ranges that cause microstructural degradation or unwanted ageing, with slower cooling through, or periods held at, those lower temperatures that allow some degree of stress relief.

One pre-requisite for successful brazing, or soldering, is the removal of oxide films and contamination that would otherwise prevent the molten filler from wetting the two surfaces and producing a good bond between them. Thorough cleaning and degreasing is always essential and there are two principal methods of removing oxide films, the use of active fluxes, and vacuum or reducing atmospheres in furnace brazing. The main disadvantage of active fluxes is the need to ensure their complete removal after brazing in order to avoid subsequent corrosion. In contrast, furnace brazing, particularly of stainless steels, gives a clean product but can cause microstructural degradation if post brazing temperatures cannot be reduced rapidly. It is in practice difficult to cool thick sections quickly enough through the critical temperature range in a vacuum furnace to prevent some sensitization.

Soldering is used to create joints at much lower temperatures, usually below about 330 C (626 F) and at these temperatures there are rarely, if ever, problems with microstructural or dimensional changes. Eutectic composition alloys are preferred where available as they freeze without going through a two-phase, pasty region that causes flow problems. The bond strengths attainable are also lower and in some of the stronger tin-rich alloys, brittleness can be created by phase changes in the tin. Bond strengths are strongly influenced by factors such as joint geometry and bond thickness, the highest strengths coming from the thinnest joints due to plastic constraint by the adjacent surfaces. It is also highly advisable to match as closely as possible the expansion coefficients of the solder and the metals to be joined, which need not necessarily be the same materials. This minimises the risk of failure due to thermal fatigue should the model have to undergo many temperature cycles between ambient and its cryogenic operating temperatures. The very low melting point alloys such as Woods metal (50Bi-25Pb-12.5Sn-12.5Cd) may have restricted use in tunnels such as the NTF where there is an operational requirement to withstand temperatures up to 95 C (200 F) as it melts between 62 and 70 C (144-156 F). However, their potential should not be overlooked for other applications where this restriction does not exist.

6. NON-METALLIC MATERIALS

Current state-of-the-art practice favours the use of metals for the construction of models for cryogenic wind tunnels, especially those for operation in pressurised transonic tunnels where aerodynamic loads can be quite large. Nevertheless, non-metallic materials have important roles to play in the construction of less highly loaded components or models and for particular applications where metals are unsuitable. In general, plastic materials have lower densities, modulii and strengths and higher expansion coefficients than metals, but in many cases they are easier to fabricate. Ceramics and glasses are stronger and stiffer, but more brittle and best used for compressive loads. Natural materials, particularly wood, are often overlooked, but they are cheap, readily available, easy to fabricate and possess a number of useful properties. For example, balsa wood has a very low density ranging from 90 to 190 kg/m^2, it is an excellent thermal insulator and has a reasonable compressive strength. Finally, it is worth remembering that one of the first models tested in the NASA Langley 7 x 11 in. low speed cryogenic tunnel was a simple sharp leading-edge 74 degree delta wing whose wings and fuselage were made from a single piece of mahogany. A reasonable finish was obtained by filling the wood and applying several coats of lacquer enamel and this combination stood up well to the cryogenic environment.

6.1 Thermoplastics

These plastics materials have long chain molecular structures in which the chains are held together by weak secondary bonds. The mechanical properties of the resultant material are highly temperature-dependent and below the glass transition temperature they are rigid and brittle. Lightly cross-linked elastomers are only able to show elastomeric behavior at temperatures abcut 20 C above their glass transition, especially when loaded dynamically. No thermoplastics have glass transitions below about 150 K, most are completely brittle at liquid nitrogen temperatures and it is only PTFE and related fluorocarbons that are of much use at low temperatures. They are used for gaskets, seals ,bearings and similar applications, but unfortunately, thermoplastics have a viscoelastic nature and they are prone to creep and stress-relaxation. Consequently they are often reinforced with fibres or powders to minimise cold flow, which also has the effect of reducing their otherwise large coefficients of thermal expansion to make them more nearly match those of the metals they are used with. The low friction characteristics of PTFE are not adversely affected by low temperatures and, when mixed with graphite and bronze powder, it forms a very useful bearing material (Glacier DQ). Fluorocarbons are also LOX compatible and thus give no problems should they inadvertently be in an oxygen-rich environment.

Thermoplastics are rarely, if ever, used in thick sections as the combination of their low thermal conductivity and high thermal expansion makes them prone to thermal shock. In the form of thin films and fibres, plastics such as mylar find uses as electrical and thermal insulators, while some thermoplastics are foamed for use as insulating materials. Probably more important, however, is their use as lacquers and adhesives, often combined with thermosetting resins. For example, epoxy-nylon adhesives are stronger than unmodified epoxies.

6.2 Thermosetting Resins

Fully cured thermosetting resins form a 3 dimensional cross-linked network structure whose mechanical properties are much less temperature sensitive and prone to creep and stress-relaxation than thermoplastics. If unfilled, they generally have very high contraction coefficients and are thus almost invariably modified unless to be used in thin layers as in surface coating lacquers. Many of the fillers used to cover the heads of fasteners, to build up complex fairings and fillets and to fair up the surfaces of wind tunnel models, are loaded thermosetting resins. The fillers are generally materials such as glass,

carbon and ceramic powders that have very small expansion coefficients and the composition is chosen so as to match that of the substrate material. The rule of mixtures:

expn. co'ft. mixture = (expn. co'ft. filler × vol. % filler) + (expn. co'ft. resin × vol. % resin)

can be used to give a good indication of the required composition, but experimental testing of a range of compositions that encompass the predicted value is usually necessary to optimize performance. Results of NASA LaRC experience on filler materials will be given in the following paper by Dr. Young.

When blown to form a closed-cell foam, many thermosetting resins form excellent insulators and some foams are also rigid enough to bear reasonable compressive loading. For wind tunnel models, foams are sometimes used in the centre of body or airfoil segments, either to fill a void or as the rigid core of a composite structure with a bonded skin of fibre-reinforced plastic forming the stressed, aerodynamically profiled surface. Probably the major uses of thermosetting resins are, however, as the matrices of the high-performance composites to be considered in the next section.

6.3 High Performance Composites

For cryogenic applications virtually all high performance composites use epoxy resins for the matrix and glass, graphite or Kevlar fibre as reinforcement. High specific strengths and moduli are obtainable using unidirectional reinforcement, while woven fibre cloths allow 2 dimensional stressed skin structures to be fabricated without too large a loss of performance compared to the unidirectional ideal. Reinforcement in 3 dimensions does, however, result in a serious lowering of the mechanical properties. The properties of a single layer of woven cloth are anisotropic, with maximum strengths and moduli along the warp and weft direction, but more isotropic properties can be obtained in laminates by varying the fibre orientations from layer to layer. Alternatively the inherent anisotropy can be utilised to enhance the mechanical and/or thermal properties in chosen directions to meet specific design requirements.

Glass fibre reinforced epoxy systems are by far the most widely used both at cryogenic and ambient temperatures where their high strengths and good toughness are desirable. Their main drawback is in their low elastic moduli and the resultant large working strains. High modulus graphite fibres can be partially or completely substituted for glass to produce stiffer composites, but their higher electrical conductivity can sometimes be a problem and even lead to galvanic corrosion if used in conjunction with more anodic metals such as aluminium. A reasonable compromise is offered by the more recently developed polyimide fibres such as Kevlar 49 which have a 45% higher modulus, a 42% lower density and similar strengths when compared to glass. This laminating cloth has a low thermal conductivity and, for a thermoplastic, a relatively low coefficient of thermal expansion, which minimises problems of differential thermal contraction between the composite and metallic alloys. Griffin (Ref. 14) has fabricated and tested a replacement forward body section for an NTF model from Kevlar/epoxy in order to compare its mechanical and thermal characteristics with those of the 18Ni 200 grade maraging steel original. Initial results appear favourable, the most serious problem involving differential thermal expansion between the dissimilar materials where the forward and main body sections join.

A preimpregnated epoxy resin/E glass cloth system was used successfully for fabricating the fan blades for the NTF and details of the system and the tests used in its verification are given in a report by Ulich et. al. (Ref. 16). Two different types of cloth having different fibre densities in the warp and weft directions were used and stacked at varying orientations in the 19 ply thick laminate. The same system has also been used at NASA LaRC to construct a 2-D airfoil for the 0.3-m TCT. The basic shape of the airfoil core was fabricated undersize, stainless steel pressure tubes were adhesive bonded into grooves machined in the core and further plies were then pressure molded over the tubes to create the required airfoil profile. Pressure orifice holes were drilled through from the surface to pick up the buried tubes and a good surface finish was obtained by hand polishing. The airfoil was then tested safely and successfully in the 0.3-m TCT at cryogenic temperatures. A similar system is also being considered for fabricating a replacement tail fin for the Pathfinder 1 NTF model.

6.4 Glass and Ceramics

Although able to withstand reasonable compressive stresses, neither glasses nor ceramics are likely to find much application in the bulk form in cryogenic models as they are brittle when loaded in tension. Pyrex glass and pyroceram do, however, have very low expansion coefficients which renders them almost immune from thermal shock and gives excellent dimensional stability. Should windows or other optical components be needed on models, Pyrex would be the logical choice. When ground to a fine powder, advantage can be taken of their low expansion coefficients in using the powder as the filler to reduce the expansion of resins and thus make the mixture compatible with metals. The use of E glass fibres for reinforcement has already been noted, but the growing use of optical fibres for communications might lead to their use for data transmission within or from a model.

The demands for higher thermal efficiencies in high temperature gas turbines and other engines had lead to considerable improvements in the strength and toughness of engineering ceramics based on oxides, carbides and nitrides. While their low temperature properties are not yet outstanding, they are improving and it would be worth keeping their development under observation. For example, machinable ceramics might have applications for lightly loaded components where their low thermal expansion and dimensional stability might be advantageous. Even state-of-the-art ceramics such as alumina could find use as bearings which can run against each other without lubrication and be stiffer than conventional metallic or polymeric systems.

7. CONCLUSIONS

Experience gained from the construction and testing of small models in the first generation of cryogenic wind tunnels, such as the 0.3m Transonic Cryogenic Tunnel at NASA LaRc, has given a valuable indication of suitable materials and fabrication techniques and highlighted some of the problems likely to be encountered. Models for the larger tunnels such as the NTF pose an even greater challenge due principally to a combination of their increased size and higher operating stresses. The required combination of high yield strength and adequate toughness at the lowest operating temperatures has severely

restricted the range of materials available. Research and development work is being carried out on improved materials to increase the strength of inherently tough alloys and to increase the toughness of strong alloys.

Earlier problems encountered with dimensional instability are now understood to have arisen due to microstructural instability in the material and the importance of choosing stable materials is now more widely understood. However, most conventional machining techniques induce surface stresses, tensile from grinding and compressive from milling, which can be quite large in alloys like A286 that work-harden rapidly. Dimensional changes can occur, particularly in thin or asymmetric sections if care is not taken to balance the surface stresses. In most model shops opposite faces are machined alternately to minimise this problem. Subsequent heat-treatment, for example as might be carried out to braze together sub-components, can upset the delicately balanced stresses and lead to warpage which could be serious enough to render the model unsuitable for testing. Furthermore, in the larger models, problems are likely to be more severe as dimensional changes, such as warpage of a wing tip, are likely to increase at least linearly with the span of the wing. The stepped specimen program has been set up to measure such dimensional changes as might be created by thermally cycling between room and cryogenic temperatures as well as to provide information on machining-induced deformation and the heat-treatments that might be used in its removal.

The development of suitable, strong bonding and joining techniques is also an area where further progress is necessary. In general, the strongest bonds are formed at the highest temperatures and in welding some of the parent metal is remelted into the fusion zone and the structure of the adjacent material in the heat-affected-zone is altered, often detrimentally. Techniques such as laser and electron-beam welding have been found useful for joining small parts such as cover plates because of their low and localised heat inputs, but they are unsuitable for many larger applications. Brazing is the most commonly utilised technique for joining model components and the correct choice of filler is very important. The highest strengths are obtained from the nickel-based alloys and they require high brazing temperatures. While this may be acceptable for alloys such as A286 which can be subsequently heat-treated to achieve their optimum properties, problems are created with their use in materials such as the 18 nickel maraging steels. These high-strength alloys must have a small grain size to ensure adequate toughness at 77 K and the grain growth that takes place at temperature above 1000 C (1800 F) would render them unsuitable for cryogenic operation. Although conventional nickel-based alloys are thus unsuitable, the recently developed nickel-palladium alloys appear to offer a satisfactory alternative. The lower temperature silver solders have been used for most model brazing operations with relative success, although some problems have been encountered due to the creation or relief of stresses during brazing or subsequent cooling.

Finally, it would appear that the use of high-performance composites such as the glass-, carbon- and Kevlar-reinforced epoxies may have an important part to play, particularly in the fabrication of the more lightly loaded parts of models. Other non-metallic materials have small, but nonetheless important, roles as seals, thermal insulation, fillers, adhesives, etc. Aluminium alloys have been used for the fabrication of simple, lightly-stressed models and copper-based alloys including bronze and beryllium copper have been used for models as well as parts such as bearings. All of these materials have different expansion coefficients and it is highly important to recognise the problems that can arise if they are used together. Tight fits can become much looser or clearances can be reduced and binding take place if dissimilar materials are cooled from room to cryogenic temperatures. Large stresses can be set up by differential thermal contraction and these stresses can lead to distortion or even failure.

It can therefore be claimed, with considerable justification, that the advances to be gained by the aerodynamicists in the attainment of high Reynolds numbers in cryogenic wind tunnels have had to be paid for in the complexity of the models to test in them. The challenges thus set to model designers and fabricators are being met and experience is accumulating on the best materials and techniques to utilize. There is still, however, much work to be done and many problems to solve and it can confidently be predicted that if a third AGARD lecture series is held on Cryogenic Wind Tunnels in another five years time, models and materials and techniques of construction will again be a major part of the programme.

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TABLE 1 Properties of Alloys used in Model Construction

No.	Property / Material	18 Ni maraging	18 Ni maraging	18Ni maraging	18Ni maraging
1	Grade	200	200 Grain-ref'd.	200Ti	250
2	Composition	8.5Co-3.25Mo-0.1Si-0.1Mn-18.5Ni 0.20Ti-0.1Al-0.01S-0.01P-0.03C		0Co-3.0Mo-0.7[illegible] 18.5Ni-.03C	7.5Co-4.8Mo-.4Ti 18.5Ni-.03C
3	Structure	Martensitic	-	-	-
4	Condition	Fully aged	-	-	-
5	Strengthening Mechanisms	Precipitation of internetallics in low-carbon martensite			
6	Corrosion Resistance	Reasonable	-	-	-
	300K MECHANICAL PROPERTIES	(t) (h) (r)	(r)	(v)	(t) (v)
7	Yield (MPa)	1418 1413 1383	1414	1379	1696 1700
	U.T.S. (MPa)	1441 1448 1411	1452	1414	1792 1895
	Elong. (%)	12(v) 10	18	13	11
	Reduction in Area (%)	65 38	57	68	38
	K_{IC} (MPa$\sqrt{m}$)	1?7 187 -	-	132	110 -
	Charpy (J)	41 48 40	51	102-115	28 27
	E (GPa)	193.7 180.7(v)		181	195.3 186.2
	Poissons ratio	.321		.311	.308 -
	77K MECHANICAL PROPERTIES				
	Yield (MPa)	1862 1716	1807		2206
	U.T.S. (MPa)	1930 1760	1883		2275
	Elong. (%)	- 8	20		
	Reduction in Area (%)	60			
	K_{IC} (MPa$\sqrt{m}$)	56 92			44
	Charpy (J)	39 34 21	33	42-43.5	14
	E (GPa)	203.0			204.8
	Poissons ratio	.304			.304
	THERMAL PROPERTIES				
	[illegible] (C) [F]	(450)	-	-	-
	[illegible] 300K (10^{-6}/K)	10.1 (v) 8.6 (g)			
	[illegible] 77K (10^{-6}/K)	6.1 (g)		-	-
	Therm. Cond. 300K (W/m.K)	19.5	-	-	25.3
	Therm. Cond. 77K (W/m.K)				
	Density (g/cc)	8.00	8.00	7.98	8.00
	HEAT TREATMENT INFORMATION				
	Atmosphere	Air, Inert, Vacuum			
	Grain Growth (C) [F]	1000 [1830]	-	-	-
	Soln. Anneal (C) [F]	815 [1500]	-	-	-
	" " Time (hr)	1hr per inch thickness, then air cool.			
	Heat-Treat. Temp. (C) [F]	480 [900]	-	-	-
34	" " Time (hr)	3 to 6 hours	-	-	-
	" " Contraction (%)	.0006mm/mm (v)	-	-	.0009mm/mm (v)
36	Sensitization (C) [F]	do not sensitize			
37	Stress Relief (C) [F]	n/a			
	DIMENSIONAL STABILITY				
	Metallurgical	Excellent	Excellent	Excellent	Excellent
39	Cryocycle (initial)	Good	*(Good)*	(Good)	(Good)
40	Cryocycle (subsequent)	Excellent	(Excellent)	(Excellent)	(Excellent)
41	Machining	Good	(Good)	(Good)	(Good)
	FABRICATION				
42	Milling Condit. A	Good	-	-	-
43	Grinding Condit. A	Good	-	-	-
44	*Surface Finish* Full Aged	Good	-	-	-
	JOINING/FINISHING				
45	Welding Process	GTA MIG EBW	Sub.arc Coated electrode		
46	Weldability	Good Good Good	Good Good		
47	Brazing Process	Vacuum Inert Gas			
48	Brazing Alloy	AWS BAg1,-3	Metglas MBF 1005		
49	Solderability	Good with correct flux			
	COST & AVAILABILITY				
50	Cost ($/lb)	8 to 10	Research alloy	6 to 8	8 to 10
51	Availability Bar	Good	n/a	Good	Good
52	" Plate	Good	n/a	Good	Good
53	" Sheet	Good	n/a	Good	Good
54	Comments	*200 Grade used for many NTF models. 77K Charpy often* low in thick sections, hence grain refinement progm. Co-free grade looks promising for future use.			Too brittle for models. Used for stings,balances
55	Data crossreferences	(t)=Ref. 22 (h)=Ref. 15 (r)=Ref. 19 (v)=Ref. 10 (g)=Ref 14			

Footnotes: Comments in () brackets are authors "best guesses" where data is unavailable or unquantified

Table 3 continued

Maraging, Ferritic and Martensitic Steels

18Ni maraging	9 Nickel	9 Nickel	12 Nickel	12 Nickel	9Ni-4Co-.2C	
300	A 353	A 553 type 1	0.3 Titanium	0.5 Aluminum	AMS-6523	1
9Co-4.8Mo-.6Ti 18.5Ni-.03C	9Ni-0.1C-0.6Mn-0.25Si-0.01S 0.02P-0.05Al-0.05Ti		12-13Ni-0.05C-.17 to .26Ti-.025Cr-.01Si	12-13Ni-0.3C-.25 to .5Al-.025Cr-.01Si	9Ni-4.5Co-.2C .35Mn-.75Cr-.7Mo	2
martensitic	ferrite-mart'te	ferrite-mart'te	martensitic	martensitic	martensitic	3
fully aged	2x norm. & temp	Qu. & temp.	Qu. & temp.	Qu. & temp.	Qu. & temp.	4
ppt in low-C ms	tempered mart't + gr.ref	tempered mart't	very fine grain	very fine grain	tempered mart't + gr.ref	5
reasonable	bad	bad	reasonable	reasonable	poor	6
(t) (v)	(lng)	(t) (lng)	(bh)	(sw)	(rp) (r) (r)	
1903 1965	656	706 [illegible]	807		1275 1288 [illegible]	7
1952 2000	830	800 770	1076		1414 1385 [illegible]	8
11	[illegible]	24	16		17 14 31..	9
[illegible] [illegible]		62	65		65 69 66.5	10
	(r) (r)	150 to 205	192		168	11
[illegible] [illegible]	168 14 187	158			81 78 12	12
190.5 189.6	195	150			198.6	13
.305	.285	.286 (g)			.296	14
[illegible]	930	1000 990	1255	1300	1497 1107	15
[illegible]	1180	1150 1140	1407		1592 1549	16
	[illegible]	24	17		12 34.5	17
[illegible]		57	61		56 41	18
	(r) (r)	164 to 152	225	243	50	19
12	99 65 138	65			18 52	20
209.3	205	207				21
.303	.28	.279 (g)				22
	470	-				23
-	11.4 (total contract'n of 9Ni					24
-	4.95 (from 300 to 77K = .19%)					25
25.3	29	28				26
	13	12.5				27
8.00					7.83	28
Air, Vacuum	Air	-			Air, Inert, Vac	29
1000 [1830]						30
815 [1500]	n/a	n/a			900,AC;816,WQ	31
1hr/in; AC	n/a	n/a			1 hr/in	32
480 [900]	899 788 586 AC	788,WQ;588,AC	685	550	550 [1025]	33
3 to 6 hr	1 hr/in	1 hr/in	2hr	2hr	4 to 8 hr; AC	34
.001mm/mm		n/a				35
	temper embrittlement 370 to 540					36
	550 to 580				538 [1000]	37
excellent	(good)	-	(good)		?	38
(good)	(good)	-	-		poor	39
(excellent)	(good)	-	-		poor	40
(good)	-		-		?	41
good	good	-	(good)		difficult	42
good	good	-	(good)		good	43
good	good	-	(good)		reasonable	44
as 200 grade	GTA MIG	SUBARC			TIG	45
"	excellent				good	46
"	?					47
"	?					48
"	?					49
8 to 10	3 to 4	3 to 4	research alloy	-	5 to 6	50
reasonable	good	good	not yet		limited	51
reasonable	good	good	available		limited	52
reasonable	good	good	commercially		limited	53
Toughness too low for most cryogenic uses.	NTF fan shaft used special 9 Ni. Poor corosion resistance means model use unlikely.		NASA developed alloy to combine high strength and toughness		limited use in 2D airfoils	54
(v) = Ref.10	(g) = Ref.14	(lng) = Ref.4	(t) = Ref.22	(r) = Ref.19	(rp) = Ref.9	55

- symbol signifies that the entry is the same as that in the previous column

TABLE 1 Properties of Alloys used in Model Construction

Stainless Steels

	Property / Material	18Cr-8Ni		18Cr-8Ni-N	18Cr-10Ni-2Mo	25Cr-20Ni
1	Grade	AISI 304L		AISI 304N	AISI 316	AISI 310
2	Composition	18/20Cr-8/10Ni-2Mn-.03C-1Si-.03S-.04P		18/20Cr-8/10Ni-2Mn-.08C-.1/.16N 1Si-.03S-.04P	16/18Cr-10/14Ni-2Mn-.08C-2/3Mo-1Si-.03S-.04P	24/26Cr-19/22Ni-2Mn-.25C-1.5Si-.03S-.04P
3	Structure	metastable aust.		stable ? aust.	metastable aust.	stable aust.
4	Condition	annealed		annealed	annealed	75% cold rolled
5	Strengthening Mechanisms	solution		solution + N2	solution	solution + C.W.
6	Corrosion Resistance	excellent		excellent	excellent	excellent
	300K MECHANICAL PROPERTIES	(w/lng)	(t)	(w/lng)	(p&b)	(w/lng)
7	Yield (MPa)	241		315	234	470
8	U.T.S. (MPa)	641		590	584	650
9	Elong. (%)	65		51	60	35
10	Reduction in Area (%)	83		75	77	
11	Kc (MPa$\sqrt{m}$)	430		340	400	
12	Charpy V (J)	217		336	169	
13	E (GPa)	200	190	(200)	195	191
14	Poissons ratio	.289		.289	.294	.305
	77K MECHANICAL PROPERTIES					
15	Yield (MPa)	427		700	445	800
16	U.T.S. (MPa)	1600		1557	1360	1210
17	Elong. (%)	46		47	56	56
18	Reduction in Area (%)	71		63	67	
19	Kc (MPa$\sqrt{m}$)	400		330	166	
20	Charpy V (J)	190		200	154	
21	E (GPa)	214	205	214	209	205
22	Poissons ratio	.278		.278	.283	.295
	PHYSICAL PROPERTIES					
23	Sp. Ht. (J/kg.C) [77K]	480	[220]	-	-	400 [200]
24	Exp. Co'ft @ 300K (106/K)	15.9	(total linear contraction of all 4 grades of stainless steel			
25	Exp. Co'ft @ 77K (106/K)	13	(between 300 and 77K is .285 percent)			
26	Therm. Cond. 300K (w/m.K)	14	16	14	14	11
27	Therm. Cond. 77K (W/m.K)	8	8.2	8	8	6
28	Density (g/cc)	8.00(p&b)		8.00	8.00	8.00
	HEAT-TREATMENT INFORMATION					
29	Atmosphere	Air, Inert, Vac.		-	-	-
30	Grain Growth (C) [F]	(1120 [2050])		--	-	(1136 [2080])
31	Soln. Anneal (C) [F]	1010/1120 [1850/2050]			-	1036/1149 [1900+]
32	" " Time (hr)	(few hours)		-	-	-
33	Heat-Treatm't (C) [F]	n/a		-	-	-
34	" " Time (hr)	n/a		-	-	-
35	" Contraction (%)	n/a		-	-	-
36	Sensitization (C) [F]	550 to 930C		-	-	-
37	Stress relief (C) [F]	480 [900];slow cool. or 950 [1750]; rapid quench				-
	DIMENSIONAL STABILITY					
38	Metallurgical	poor, (Ms=230K)		good, (Ms=100K)	medium, (Ms=160K)	exc., (Ms=30K)
39	Cryocycle (Initial)	(good?)		(very good)	(good)	(excellent)
40	Cryocycle (Subsequent)	(very good)		(excellent)	(very good)	(excellent)
41	Machining	poor, (Md =400K)		good, (Md=250K)	medium, (Md=300K)	exc. (Md=200K)
	FABRICATION					
42	Milling	poor		-	-	-
43	Grinding	poor		-	-	-
44	Surface Finish	reasonable		-	-	-
	JOINING/FINISHING					
45	Welding Process	MIG, TIG, SMAW		-	-	-
46	Weldability	excellent		-	-	-
47	Brazing Process	Vacuum or Inert Gas				
48	Brazability Alloy	AWS BAG 1,3, AWS BNi 3.				
49	Solderability	Good with reactive flux, for example orthophosphoric acid.				
	COST & AVAILABILITY					
50	Cost ($/lb)	4		5	4	6
51	Availability Bar	excellent		good	excellent	good
52	" Plate	excellent		good	excellent	good
53	" Sheet	excellent		good	good	good
54	Comments	300 series stainless steels widely used for cryogenic tunnel fabric'n. Have been used for lightly stressed cryogenic models but too weak for higher loads in pressurised tunnels such as NTF.				
55	Data References	w = Ref.2		(p&b) = Ref. 11	(lng) = Ref.4	

Footnotes: Comments in () brackets are authors "best guesses" where data is unavailable or unquantified

Table 1 Continued

Stainless Steels

21Cr-6Ni-9Mn	25Cr-13Ni-.4N	A286	PH13-8Mo	15-5PH	17-4PH	
Nitronic 40	JAERI SUS 170	AMS-5736A	UNS S13800	UNS S15500	UNS S17400	1
21Cr-6Ni-9Mn- .15?.3N-.3V-1Si [illegible]	25Cr-13Ni-.40N- .2Mo-.5Mn-.9Si- .02C-.03P-.002S	25Ni-14Cr-2.2Ti 1.2Mo-1.5Mn-.3V .08C-.2Al-.5Si	13Cr-8Ni-.04C- 1.1Al-2.2Mo- .03Mn-.03Si	15Cr-4.5Ni-.04C 3.4Cu-.4Si-.3Mn .25Nb	16.5Cr-4Ni-.04C 3.4Cu-.6Si-.3Mn .25Nb	2
stable? aust.	stable? aust.	stable aust.	martste + aust	ms. + rev. aust	ms. + rev. aust	3
annealed	annealed	STA	H 1150 M	H 1150M	H 1150 M	4
solutes + N2	solutes + N2	precipitates	ppt.+ temp. ms.	ppt.+ temp. ms.	ppt.+ temp. ms.	5
excellent	excellent	excellent	excellent	excellent	excellent	6
(a) (h)	(sak)	(t) (rp) (h)	(a) (h)	(a)	(a)	
400 483	460	750 690 689	586 586	717	586	7
710 758	861	1000 1103	896 896	896	862	8
50	52	24	22	23	22	9
70	75	37	70	75	68	10
		114/161 132	165			11
294 271	477	(g) 75	162 109	136	135	12
197		195.8 200.6	172	196	201	13
.285		.330 .306	.278	.272	.291	14
		(t)				
1034 1034	1131	930 827	1000	1007		15
1400 1379	1693	1482	1207	1336		16
	46			27		17
24	63			65		18
182		121				19
87 88	243	68	81	27	7	20
		202.7 (g)				21
						22
				418	460	23
16.7		16.7	10.9	11	11	24
		12.2(g)				25
13.4		14.9	12.7	17.9	(15)	26
(5)						27
7.83		7.96	7.76	7.82	7.82	28
Air, Vac, Inert	-	-	-	-	-	29
1180 [2150]		(1180 [2150])	(1180 [2150])	1180 [2150]	1200 [2200]	30
1066 [1950]		982 [1800]	927 [1700]	1030 [1900]	1030 [1900]	31
1 hr/in; + W.Q.		1 hr then W.Q.	30 min. + A.C.	30 min. + A.C.	30 min. + A.C.	32
not relevant		734 [1350]	760,AC; 620,AC.	760,AC; 620,AC.	760,AC; 620,AC.	33
" "		16 hr then A.C.	2 hr ; 4 hr	2 hr ; 4 hr	2 hr ; 4 hr	34
			.0035	.0024	(.002-.003)	35
590/930 [1100/1700]		(- ?)	(- ?)	(- ?)	(- ?)	36
480[900],AC or	950[1750],WQ.	Solution anneal	then re-age	-	-	37
Stable		Stable	Stable ?	Unstable	Unstable	38
Good		Excellent	Some warpage	Large warpage	Large warpage	39
Excellent		Excellent	Excellent	Further warpage	Further warpage	40
High stress		V. High stress	Moderate stress	?	?	41
poor		bad	harder than 304	like 304	like 304SS	42
poor		poor	good	" "	" "	43
soft		reasonable	Very good	Excellent	Excellent	44
MIG, TIG, SMAW	-	- weld in	TIG	MIG, TIG, SMAW	-	45
Good	-	soln treat cond	Good	Good	-	46
Vacuum, Inert Gas		-	-	-	-	47
AWS BAg 1,3; AWS BNi 3;		soln. HT; reage	-	-	-	48
Good with reactive flux, for example		orthophosphoric acid		-	-	49
5		9	7	7	7	50
Difficult	?	Long lead time	Long lead time	Reasonable	Reasonable	51
Difficult	Up to 60mm	"	"	"	"	52
Reasonable	Down to 0.3mm	Reasonable	"	"	"	53
Used for Pathfinder 1 and other NTF models	Alloy developed in JAERI fusion research prog.	Many 2 & 3 D models used in La RC 0.3m and NTF tunnels	Alloy must be cooled 16 [60] before ageing NTF model use	Alloys must be cooled 32 [90] before aging to complete marten-	site transformation. Unstable in H1150M, too brittle fully aged.	54
(a) = Ref. 8	(sak) = Ref. 20	(rp) = Ref. 9	(t) = Ref. 22	(h) = Ref. 15	(g) = Ref. 14	55

- symbol signifies that the entry is the same as that in the previous column

TABLE 1 Properties of Alloys used in Model Construction

Aluminium and Copper Alloys

	Property \ Material	Aluminum	Aluminum	Aluminum	Beryllium Copper
1	Grade	AAA5083	AAA6061	AAA 2014	
2	Composition	4.5Mg-.6Mn	1Mg-.6Si-.27Cu-.25Cr	4.4Cu-.8Si-.8Mn-.4Mg	1.8Be-.2Co-.1Fe-.1Si
3	Structure	f.c.c	f.c.c	f.c.c	f.c.c
4	Condition	annealed	T6	T6	soln HT & aged
5	Strengthening Mechanisms	solution	precipitation	precipitation	precipitation
6	Corrosion Resistance	*good*	*good*	*good*	*good*
	300K MECHANICAL PROPERTIES	(lng)(ml3)(asm)	(lng)(m63)(asm)	(lng)(ml3)(asm)	(m63)
7	Yield (MPa)	150	270	420	667
8	U.T.S. (MPa)	313	306	476	702
9	Elong. (%)	23	18	13	19
10	Reduction in Area (%)	35	56		68
11	Kc (MPa m)				
12	Charpy V (J)		22		51(U)
13	E (GPa)	71.6	70.2	73.1	131
14	Poissons ratio	.3334	.3383		
	77K MECHANICAL PROPERTIES				
15	Yield (MPa)	164	330	470	819
16	U.T.S. (MPa)	434	412	565	909
17	Elong. (%)	33	24.5	14	31
18	Reduction in Area (%)	38	51		66
19	Kc (MPa m)				47(U)
20	Charpy V (J)		22		
21	E (GPa)	80.2	77.1		
22	Poissons ratio	.3195	.3277		
	PHYSICAL PROPERTIES				
23	Sp. Ht. (J/Kg.K) [77]	966 [340]	966 [340]	966	420
24	Exp. Co'ft 300K (10-6/K)	23.2 23.4	23.2 23.4	23	17.8
25	Exp. Co'ft 77K (10-6/K)	9.0	9.0		
26	Therm. Cond. 300K (W/m.K)	115 118	193	218	84
27	Therm. Cond. 77K (W/m.K)	55			
28	Density	2.66	2.7	2.8	8.23
	HEAT-TREATMENT INFORMATION				
29	Atmosphere				
30	Grain Growth (C) [F]				
31	Soln. Anneal (C) [F]			496/507 [925/945]	
32	" " Time (hr)			1 hr (salt), air	
33	Heat-Treatm't (C) [F]			168/174 [335/345]	
34	" " Time (hr)			8 to 12 hr	
35	" Contraction (%)		none?	-	.2
36	Sensitization (C) [F]	Aluminium alloys do not sensitise		-	
37	Stress Relief (C) [F]			360/412 [650/775]	
	DIMENSIONAL STABILITY				
38	Metallurgical	Excellent	Excellent	*Good*	*Good*
39	Cryocycle (Initial)	Good	Good	Good	Good
40	Cryocycle (Subsequent)	Good	Good	Good	(good?)
41	Machining	Aluminium alloys	similar to 300	series stainless	(good?)
	FABRICATION				
42	Milling	Poor	Fair	Good	Poor
43	Grinding	Aluminium alloys	not normally ground		?
44	Surface Finish	Poor	Fair	Good	Fair
	JOINING/FINISHING				
45	Welding Process	MIG, TIG, SMAW,	-	-	MIG, TIG,
46	Weldability	Good	Good	Fair	Excellent
47	Brazing Process	Not normally recommended for aluminium alloys			Furnace, torch
48	Brazability Alloy	"	"	"	Good, Ag-based
49	Solderability	Very agressive fluxes needed, not recommended			Excellent
	COST & AVAILABILITY				
50	Cost ($/lb)	2-3 $/lb	-	-	5-6 $/lb
51	Availability Bar	Good	Good	Good	Reasonable
52	" Plate	Good	Good	Good	Reasonable
53	" Sheet	Good	Good	Good	Reasonable
54	Comments	Used in bulk in tankage. Limited model usage	Used for lightly loaded models in 0.3-m TCT & NTF	Stronger but lower toughness limits model use	Used for high thermal conductivity inserts.
55	Data References	(lng) = Ref. 4	(ml3) = Ref. 6	(asm) = Ref. 5	(m63) = Ref. 7

Footnotes: Comments in [ ] brackets are authors "best guesses" where data is unavailable or unquantified

Table 1 Continued

Titanium, Low Expansion and Nickel Superalloys

Ti-6Al-4V	Ti-5Al-2.5Sn	Invar	Ni-Span C	Inconel 718	Inconel X750	
Ti-6Al-4V,ELI	Ti-5Al-2.5Sn,ELI	Nilo36, Nilvar	Constant Modulus 42			1
6Al-4V-.1Fe-.01C	5Al-2.5Sn-.2Fe-.07C	36Ni-.1C-.36Si-.35Mn-.1Al-.015P-.015S	42Ni-5.2Cr-.5Al 2.4Ti- .06C	19Cr-18.5Fe-3Mo .9Ti-5.1Nb & Ta	15.5Cr-7Fe-.7Al 2.5Ti-.95 Nb & Ta	2
h.c.p./b.c.c.	h.c.p.	f.c.c.	f.c.c.	f.c.c.	f.c.c.	3
Annealed	Annealed	Annealed	Soln.HT & aged	Soln.HT & aged	Soln.HT & aged	4
Solute /2 phase	Solution	Solution	Precipitation	Precipitation	Precipitation	5
Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	6
(g) (n) (h)	(h) (n) (t)	(lng) (h) (t)	(m63) (asm)	(t) (h) (asm)	(h) (asm)	
951 896	724 875	276 289	774 793	1172 1034	758	7
1024 931	827 925	552 552	1202 1240	1404 1276	1241	8
17	19	55	24 18	20		9
47	44		50			10
96.9 100 (t) 90	90 101			90		11
27 37 27	34 24 34(g)	298	24 (t)	27	47.5	12
110.3 111	111	153 152	182	213	213	13
.330	(.330)	.2845				14
1576 1310	1207 1380	621 620	905	1207	862	15
1624 1413	1241 1437	862 862	1550	1620	1482	16
10	14	42	31.6			17
41	30		47			18
59 61 (t) 61	72 75			110	110	19
14 21 14	14 15 14(g)	68	23 (t)	27	47.5	20
121.4	(121.4)	140.4 141		227	227	21
		.307				22
(530) ([200])	530 ([200])	(asm) 517 ([190])		(450 [170])		23
(9.3)	9.36 8.4/9.4	1.2 2.5		11.5		24
		0.4 .83				25
(8.17)	8.17	13.8 13.8		0.1 to	0.23	26
(4.4)	4.4	6.2 6.2		.058 to	0.16	27
4.43	4.46	8.0		(8.2)	8.3	28
Vacuum, Inert Gas		Reducing/inert atmosphere		Inert, Air	-	29
ph tr. T = 1000	760 [1400]					30
843/954 [1550]	815 [1500]	750/850 [1380]	(- ?)	980, A.C.	980, A.C.	31
15/30 min;W.Q.	30 mins	30 min/in; W.Q.	(- ?)	1 hr	1 hr	32
480/540 [900]	n/a	315 95	650 730	720,FC; 620,AC	870,ac; 705,AC	33
4/8 hr; A.C.	n/a	1hr,AC; 48hr,AC	5 hr 3 hr	8 hr ; 20 hr	25 hr ;20 hr	34
n/a	n/a	n/a		0.09%	0.09%	35
do not sensitise		do not sensitise	-	Do not sensitise		36
704/829;1-2 hr	540/650;1-2 hr	same as heat-treatment		870 for 3 hr to 980 for 7/15 min		37
(stable)	stable	stable	stable	stable	-	38
(good)	(good)	(-)	(-)	(stable)	-	39
(good)	(good)	(-)	(-)	(")	-	40
						41
difficult	difficult	(like 304?)	(poor)	difficult, work hardens rapidly		42
fine,dry swarf is inflamable !		(" " ?)	(reasonable)	reasonable		43
poor ?	poor ?	Reasonable ?	(" ")	easily scratched		44
MIG, TIG, EBW	-	MIG, TIG	- ?	TIG, MIG, SMAW,	-	45
Excellent	-	good	- ?	good	-	46
Vacuum, Inert Gas		?	- ?	Vac, Inert, Air	-	47
Care needed	-	?	- ?	Copper alloys prefered to silver		48
not usual	-	active flux	- ?	Acid flux for Pb & Sn solders		49
6 to 9 depending on product form		9	10	12	12	50
reasonable	-	reasonable	poor	difficult	-	51
reasonable	-	"	"	not available	-	52
good	-	"	"	difficult	-	53
Poor low temperature toughness and difficult machinability combine to make titanium unattractive for cryogenic models		Total contraction from 300 to 77K =0.05%, 10% of steels.	Used in springs & bellows, too brittle for general use.	High cost and extreme difficulty in machining, drilling and fabrication restrictusage to high temperature models.		54
(n) = Ref. 6	(g) = Ref. 14	(t) = Ref. 22	(asm) = Ref. 5	(m63) = Ref. 7		55

- symbol signifies that the entry is the same as that in the previous column

Design and Construction of Models for the National Transonic Facility - I

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Summary

The design and construction of models for the National Transonic Facility (NTF) has resulted in significant technology developments in many areas. This lecture covers the development of design criteria and major research and development work that has contributed to the successful design and fabrication of models for testing at full scale Reynolds number in the NTF. Emphasis is placed on the materials aspect of the design and fabrication process, including metallic materials, mechanical properties characterization, new steel alloy development, fracture toughness enhancement, and identification of fillers and solders suitable for use in cryogenic models. Quantitative data are provided which will be of value to the potential user of NTF or for application to the design and fabrication of model systems for other cryogenic wind tunnels.

1.0 Introduction

The advent of High Reynolds number testing in the cryogenic National Transonic Facility (NTF) at the NASA Langley Research Center (LaRC) has given rise to unprecedented difficulties in the design and fabrication of model systems for the new facility. In 1979, a program for development of technology for cryogenic model systems design and fabrication was initiated. The basic objectives were to identify and address the technological problems associated with the design and fabrication of model systems for use in NTF, and develop new technology where needed. In order to accomplish these objectives, developmental models (Pathfinders I and II) were chosen for design and fabrication at the Langley Research Center. In addition, a contractual study[1] was initiated to investigate the design feasibility of maneuvering aircraft models having thin instrumented wings, flow-through engine simulation, and moveable controls.

The aforementioned tasks were used as the basis for addressing design difficulties such as those associated with the severe thermal environment, potential for brittle fracture, high dynamic pressure loads, and stringent fabrication tolerances.

Various aspects of the work presented herein have been reported in previous conferences.[2,3,4] Most of the work reported on previously,[2,3,] had not progressed to the point where quantitative data were forthcoming. The data presented in this lecture are taken largely from reference 4. The purpose of this lecture is to report on the evolution of design criteria for NTF models and to present the results of metallic alloy studies aimed at developing and characterizing materials suitable for cryogenic use. Also, studies related to filler material selection and solder applications are presented. Where available, quantitative data are provided along with fabrication and operational experience gained to date.

2.0 Design Criteria

Design Criteria have been developed specifically for NTF models. The criteria define special requirements for utilizing the high Reynolds number capability of the NTF. The criteria are set forth in reference 5 and are mandatory for testing in the NTF. However, deviations from the criteria are allowed contingent upon the NTF Facility Safety Head approval.

2.1 Evolution

The criteria basically evolved from the NTF developmental model activity which forced the model(s) design to be able to be tested at full scale Reynolds number, high dynamic pressure, and at cryogenic conditions.

2.2 Allowable Working Stress

Two sets of allowable working stress criteria are given in reference 5. Where possible, working allowables of 3 on yield or 4 on ultimate (method 1 approach, ref. 5, worst case loads, with stress concentration) makes life simpler for the analyst. However, many models for NTF will require designing to lower safety factors. The safety factors allowed per reference 5 are summarized in table 1. The method 2 approach (lower safety factor(s)) of reference 5 is intended to provide a systematic way of designing for various types of stresses (e.g. membrane, bending, etc.) and gives criteria for combining stresses for various types of loads conditions (e.g., thermal and mechanical). The approach is not new but rather is based on criteria used for optimal design of highly loaded structures using the maximum shear stress criteria for failure. For example, the design of Pathfinder I (figures 1 and 2) to the test condition illustrated in figure 3 resulted in a localized working stress of approximately two-thirds of the yield strength of the material. Thus, it became obvious early on that the use of LaRC conventional safety factors of 3 on yield and 4 on ultimate could not be maintained utilizing currently available metallic alloys. As a result, criteria were developed which would allow the model to be designed to lower safety factors without compromising structural integrity. The use of lower safety factors for design necessarily requires more in-depth analysis, with particular emphasis on the potential for brittle fracture failure.

In cases where fatigue is a major consideration, allowable cyclic stress is obtained by reducing the fatigue strength by a factor of 2 and the analysis must account for mean stress and stress concentration effects.

2.3 Fracture Toughness

For purposes of material selection, all steel alloys for critically stressed components must have a fracture toughness (K_{Ic}) of at least 85 ksi-in$^{1/2}$ at test temperature in the as-built condition. In lieu of K_{Ic}, Charpy V-notch (C_{VN}) criteria are given in ref. 5 in terms of foot-lbs. required as a function of material minimum tensile strength. Generally, the higher the tensile strength, the greater C_{VN} value required. For example, materials having tensile strength greater than 95 ksi are required to average 25 ft-lbs. for three specimens. Some materials do not undergo a marked drop in fracture toughness and are not required to meet the K_{Ic} and C_{VN} requirement. These materials include aluminum alloys, copper and its alloys, nickel and its alloys. It should be noted that the Charpy V-notch requirement is aimed at selecting materials for use at high stress levels and serves primarily for screening materials and should not be used for eliminating other materials. Also Charpy V-notch data are more readily available than K_{Ic} data and serves as a comparatively easy test certification.

2.4 Fracture Mechanics Analysis

A fracture mechanics analysis is required to estimate the acceptable flaw size in the actual part based on design life requirements. This can be used as a basis for establishing the non-destructive examination (NDE) standards. Alternatively, given that a material can be inspected to a certain flaw size standard, the screening flaw size is used in the fracture mechanics analysis to calculate the useful life (cycles to failure) compared to the design requirement. A key element in the fracture assessment is the determination of NDE standards which will assure a good inspection.

2.5 Non-Destructive Examination Standards for Critically Stressed Cryogenic Model Metallic Alloys

It is imperative that all metallic alloys used for NTF models be given a 100 percent volumetric nondestructive examination. The presence of flaws in the model structure, particularly for highly stressed components could severely jeopardize the model system structural integrity. In order to arrive at a standard which meets criteria for performing fracture mechanics analysis and for materials procurement, Berry[6] developed ultrasonic inspection specifications for use in procuring NTF model materials. Both straight beam and angle beam inspection specifications were formulating. Berry developed a novel method for use as an angle beam reference standard. The use of a letter "I" steel die stamp was found to be a very simple, cost effective and easy standard to use for this type of inspection, and is currently being used by LaRC for procurement of cryogenic metallic alloys. The radiographic and surface inspection specifications for metallic alloys as well as the inspection requirements for composite materials are given in reference 5.

2.6 Stability

Testing at higher dynamic pressures (compared to most conventional high-speed, low R_e models) requires that added attention be given to aeroelastic stability both static (divergence) and dynamic (flutter). For testing in NTF, a safety factor of two(2) is required against divergence and flutter. Stability analysis methods are left

to the user and should reflect state-of-the-art methodology. It is important to note that the aeroelastic analysis should include balance flexibility. Based on experience to date in designing model systems, the chief limiting factor on designing to the desired test envelope is divergence. Also many systems are likely to be balance load-limited as well. The stability criteria are summarized in table 1.

3.0 Engineering Design and Fabrication Research and Development

The principal areas of investigation are discussed in this section. In general, a description of the various activities is provided and where available, quantitative and/or qualitative data obtained from R&D work conducted to date are presented.

3.1 Fatigue and Fracture Toughness Characterization of Primary Steel Alloys

Over the past several years, fatigue crack growth and fracture toughness tests were conducted at LaRC for several candidate materials for use in NTF model systems. Of particular significance is the work reported by Newman and Lisagor[7] on Nitronic 40 (Pathfinder I material) stainless steel and the 18 Ni grades 200 and 250 maraging steel.

Fracture toughness test results on the Nitronic 40 in both the as-received and stress relieved condition more that met the cryogenic models toughness criteria (85 ksi-in$^{1/2}$) for this type of alloy. Whereas, it was determined that the 250 grade maraging steel did not meet the aforementioned criteria, the 200 grade maraging steel was found to be marginal, but acceptable.

The need for adequate material strength, fatigue, and fracture toughness properties for model systems to be tested in the NTF requires that a comprehensive data base be established at cryogenic temperatures. For example, in the case of the 18 Ni grade 200 maraging steel, fatigue crack growth propagation data were not available at cryogenic temperatures. Also, fatigue testing of this material had not been accomplished at cryogenic temperatures. Because of the heavy investment in this material for NTF balances[8] and the large number of NTF models utilizing this material, it became imperative that the material properties be characterized at cryogenic temperatures, for the appropriate heat treatments, including the grain refined condition (discussed in a subsequent section in this lecture). In particular, the NTF strain gage balance design criteria requires a safe-life design for which fatigue data were needed for useful life assessment. In addition, these tests were designed to obtain both Charpy V-notch and fracture toughness data. This information can also be used to evaluate the adequacy of the empirical relationship between the fracture toughness parameter K_{I_c} and Charpy V-notch impact energy C_{V_N} (see ref. 9). Also cryogenic crack growth data were needed to perform the fracture mechanics assessment.

The current test program utilizes approximately 225 (in total) fatigue, fracture toughness, Charpy V-notch, and tensile specimens for the 18 Ni 200 grade maraging steel alone. Testing was done at both room and cryogenic temperatures. A similar test program is planned for the A-286 and 13-8 Mo stainless steel materials. The specimens were taken from both plate and bar stock material with orientations as illustrated in figures 4 and 5.

3.1.1 18 Ni Grade 200 Maraging Steel

Results of fatigue and fracture toughness testing of 18 Ni Grade 200 Maraging Steel are reported by Wagner in reference 10. Elastic modulus was statically determined using the dead weight method at room temperature, at -275°F and at intermediate test temperature of -100°F and -200°F as given in table 2. As expected, there is a slight increase in modulus with decreasing temperature. Trends in tensile test results are given in table 3 and are consistent with tensile properties reported by the manufacturer. The tensile properties of 18 Ni steel achieved through grain refining are also shown in table 3. Charpy V-notch data are given in figure 6 for the plate specimens and reflect a slight gain in energy absorbed in the grain refined condition at -275°F for all orientations chosen. In addition, fatigue cracking of sharp-notch bend specimens was carried out at room and cryogenic temperature to establish crack growth behavior at various stress intensity (ΔK) levels. Subsequently, these specimens were loaded to failure to determine fracture toughness values. Fracture toughness data ($K_Q = K_{I_c}$) on bar and plate material are given in figure 7.

Fatigue data are presented in figure 8 for both room and cryogenic temperatures (-275°F). The material exhibits good fatigue strength properties with the endurance limit (fatigue strength at 10^6 cycles) being approximately 50 percent of ultimate. Also, it should be noted that the material exhibited excellent resistance against crack initiation, which is of particular significance for use in NTF balances.

Although the 18 Ni 200 Grade material is seen to be marginal insofar as meeting the fracture toughness criteria, the excellent strength, dimensional stability

(Wigley)[11] and machining properties, make it a good choice for NTF models. Also, the potential for toughness improvement via grain refinement makes this material even more attractive.

3.2 Grain Refinement

Many existing commercial high strength steels need additional fracture toughness to meet current criteria for use in NTF model systems at test temperatures approaching that of liquid nitrogen (-320°F). A program was conducted at LaRC to explore the possibility of "toughness enhancement" for available high strength steels through the use of multi-step heat treatments to refine or reduce the grain size (ref. 12). The relationship between fine grain size and improved low temperature toughness has been long established, however, a suitable technique for developing this fine grained structure in high strength martensitic and maraging steels was desired.

Grain refining heat treatments for the medium strength ferritic alloys Fe-12 Ni and 9 Ni by Morris[13,14] have demonstrated an excellent combination of strength and toughness for these alloys at cryogenic temperatures. The LaRC program goal was to determine if similar improvements could be realized for the higher strength martensitic alloys with particular emphasis on HP 9-4-20 and 18 Ni Grade 200 maraging steel.

3.2.1 Process

The grain refining process consists of multiple heating and cooling cycles alternating between the austenite (γ) and the dual-phase austenite-plus-ferrite ($\gamma + \alpha$) region, followed by rapid cooling to reduce the grain size. The grain refinement cycles are followed by annealing and age hardening or tempering as required to restore strength. (See fig. 9.) The grain refining temperatures were determined from the alloy phase diagram where available, and from the iron-nickel equilibrium and transformation diagrams (figures 10 and 11). Cycle times (time at temperature) were set at 1 hour for the 12 in. x 12 in. x 1 in. (approximately 40 lbs.) specimens used in this investigation with the specimen temperature being monitored by a thermocouple installed in a hole drilled to 1/2 plate thickness.

The five alloys studied in this investigation were 9 Ni ferritic alloy, HP 9-4-20 and HP 9-4-30 (Ni-Co high strength martensitic alloys), AF-1410 (Ultra-high-strength pseudo-maraging steel); and 18 Ni 200 Grade (Ultra-high-strength fully maraging steel). The grain sizes of all alloys except AF-1410 were reduced significantly by this technique with the greatest reduction being observed for HP 9-4-20 and 18 Ni 200 Grade. The grain sizes of these two alloys were reduced to 1/10 of original size or smaller, (60 to 80 micron grains being reduced to 6 to 8 microns was typically observed for these alloys (figures 12 and 13)).

3.2.2 Properties Achieved

The toughness as measured by charpy impact energy tests (C_{V_N}) increased for all alloys investigated at both room temperature and -320°F. The largest increase in C_{V_N} at -320°F was observed for HP 9-4-20 with an increase of 180 percent (13-14 ft.-lbs. to 38-39 ft.-lbs.). The C_{V_N} energy of 18 Ni 200 Grade increased 52 percent at -320°F (15-16 ft.-lbs. to 24-25 ft.-lbs.). Although a 71 percent increase in C_{V_N} was observed for AF-1410 at -320°F (7 ft.-lbs. to 12 ft.-lbs.) this increase could not be attributed to alterations of the grain structure and must involve some other mechanism in its complicated alloy system. The C_{V_N} and tensile strength data for all alloys are summarized in figure 14.

The yield strengths of the various alloys at -320°F were altered by grain refining from a reduction of 25 percent for HP 9-4-20 to an increase of 5 percent for the 18 Ni 200 Grade. The tensile strength variation for the grain refined materials ranged from a 3 percent loss for HP 9-4-20 to a 7 percent increase for the 18 Ni 200 Grade at -320°F. Both materials displayed increases of over 100 percent in their elongation at -320°F in the grain refined condition, with reduction in areas being increased 38 percent for HP 9-4-20 and 76 percent for the 18 Ni 200 Grade.

The grain refined HP 9-4-20 displayed a completely "dimpled rupture" type of fracture at -320°F compared to the normal quasi-cleavage fracture mode for this material in the stock condition (fig. 15). The fracture mode observed for 18 Ni 200 Grade at -320°F for both stock (as-received) and grain refined material appeared to be microvoid coalescence (typical of alloys of this strength level) with a larger number of small fracture sites and more extensive plastic straining between microvoids being observed for the grain refined material (fig. 16). The fracture surfaces observed for both alloys are indicative of a significant improvement in toughness at -320°F compared to the stock material.

Due to the large increase in toughness observed in HP 9-4-20 and the improved strength and toughness observed in 18 Ni 200 Grade these two alloys have been chosen for further grain refining experiments at LaRC. Also, dimensional stability studies are currently underway on grain refined HP 9-4-20 to determine its suitability for high precision components at -320°F. Future plans call for the expansion of grain refining to other alloys groups such as the precipitation hardened stainless steels and the maraging stainless steels.

3.2.3 Machinability

An unexpected but highly beneficial side benefit from grain refining was improved machinability. The machinability of all alloys was improved after receiving the grain refining treatment with higher removal rates and smoother surfaces being produced compared to the stock materials. This improved machinability should reduce fabrication cost significantly for high precision cryogenic wind-tunnel models.

3.2.4 NTF Model Application

As a result of the experience gained from the grain refinement studies, the process was applied to the fuselage/wing section of the .01 Shuttle model shown in figure 17. In this application, approximately 450 pounds (4 x 16 x 24 in.) of 18 Ni Grade 200 in the annealed condition was grain refined per figure 9 through step 5 (anneal). Grain size reductions with equivalent to that experienced with the 50-pound specimens. A major benefit derived from this application was improved machinability. It is estimated that the machining costs for this component were reduced by 25 to 30 percent, which is a significant savings. Also, dimensional stability was found to be excellent throughout the machining process.

3.3 12 Percent Ni Cryogenic Steel Production Development Program

3.3.1 Previous Research

An experimental iron based alloy developed by NASA at the Lewis Research Center (LeRC)[15] combines the normally divergent properties of high strength and high toughness at cryogenic temperatures. The research at LeRC revealed that high toughness at cryogenic temperatures could be achieved in Fe-12Ni alloys through the addition of small amounts of reactive metals such as Al, Nb, Ti, and V. Further research at LeRC by Stephens and Witzke[16,17] demonstrated that high yield strength (200 ksi) together with high toughness (200 ksi-in$^{1/2}$) could be achieved at -320°F in a single alloy by thermomechanical processing (TMP) or by precipitation hardening through the addition of copper. Of the 35 different alloy compositions investigated, two were deemed worthy of further study, Fe-12 Ni Al and Fe-12 Ni Ti. Both alloys contain 12 percent Ni and either .5 percent Al or .25 percent Ti with the balance being iron.

Close control of alloy composition with low interstitial impurities must be maintained if the high strength/toughness properties are to be realized. Close chemistry and impurity control had been realized in 2 lb. laboratory ingots at LeRC and in larger 350 lbs. ingots produced by Carnegie-Mellon Institute of Research on contract to LeRC.[18] The Langley program goal was to produce large multi-tonnage ingots and process them into 1-, 2-, and 4-inch thick plates and 6- and 4-inch diameter bars. The program sought to use established commercial steel making processes and techniques to gain an experience base for possible future commercialization. Carnegie-Mellon was awarded a contract by LaRC for the production of approximately 10,600 lbs. (5,300 lbs. each) of the two alloys.

3.3.2 Production

Carnegie-Mellon proposed producing the material by air induction melting (AIM) with argon-oxygen decarburization (AOD) followed by electroslag remelting (ESR) to ensure high purity material. The hot rolled plates and bars are then strengthened by TMP (cold rolling and annealed). The TMP process was chosen over the copper precipitation hardening due to the simpler alloy composition. The chemical composition specification for the alloys is shown in table 4 and illustrates the close control of alloying elements and impurities desired.

The program was divided into three phases: Phase 1. Initial melting of approximately 14,000 lbs. of charge material using AIM/AOD to produce two 6,400 lbs. ingots (one of each alloy). Phase 2. Pilot ESR program of approximately 400 lbs. of each alloy with TMP to verify that the desired properties can be obtained. Phase 3. Production ESR melt and TMP of remaining material to produce required bar and plate material.

The chemical analysis of the large ingot initial melts showed all alloying elements and impurities within the desired range except for carbon. The analysis showed 70 parts per million (PPM) for the Ti alloy and 30 PPM for the Al alloy

compared to the 400 to 600 and 100 to 500 PPM ranges desired, respectively. (See table 4). Stephens[11] had reported a severe loss of low temperature toughness for 12 percent Ni steels if the carbon content is below 100 PPM (see fig. 18 taken from ref. 19). Carnegie-Mellon proposed correcting the carbon deficiency during the ESR phase through the addition of carbon-rich iron shot. This technique was verified in the ESR pilot melt (phase 2) and was incorporated into the final production melt.

3.3.3 Properties Achieved

Fracture toughness properties obtained from the final production melt (two 6,400 lb. ingots) were greater than anticipated and are illustrated in figure 19. In particular, the Titanium alloy achieved values greater than 400 ksi-in$^{1/2}$ while the Aluminum alloy was in the range of 350 ksi-in$^{1/2}$. These toughness values were accompanied by some loss in strength (when compared to the expected values). Since the toughness was higher than needed, the material annealing schedule was increased by approximately 122°F for the Titanium alloy and 275°F for the Aluminum alloy in an attempt to improve strength properties, while reducing toughness. The expected toughness, however, should still far exceed the requirements and allow for higher strength design applications.

The material in the form of plate stock is in the process of final delivery to LaRC. Studies will be conducted to examine the dimensional stability (previously discussed by Wigley)[20] machining characteristics, and general suitability of the material for construction of models (including balances) for NTF. However, the delivered finished plates is expected to offer a combination of strength and toughness at -320°F unmatched by any existing commercial available alloy.

3.4 Filler Materials

The high Reynolds Number capability of the NTF has imposed stringent requirements for model surface finishes. At present, filled areas for NTF models are expected to require high quality finishes in the range of 15 to 20 micro inches rms. Fillers that are commonly used to smooth imperfections such as joints and fastener holes for conventional (non-cryogenic) wind tunnel models include polyester resins, plasters, and waxes, which are generally unsuitable for use in the NTF due to low temperature embrittlement and thermal mismatch.

Previous work at LaRC during the Pathfinder I program identified a filler material composed of EA-934 epoxy resin plus aluminum powder mixed 1:2 by weight (1 part epoxy, 2 parts aluminum) as being a suitable filler material for cryogenic models. Subsequent studies at LaRC[21] and experience by private industry[22] have found that this mixture while having good adhesion and retaining a reasonable surface finish at -320°F, has a coefficient of expansion significantly greater than the commonly used metals for model construction (ref. 21). This expansion mismatch leads to depressions in the filler material below the desired contour and can result in bondline failure of thick sections (fig. 20).

The criteria for the current cryogenic filler material investigations at LaRC are as follows: (1) The filler material must closely match coefficients of expansion for metals used in model construction; (2) be easily hand worked and readily removeable for model changes and maintenance; (3) provide a smooth high quality, finish (15-20 rms) over the temperature range of the NTF; and (4) remain structurally intact during thermal and structural load cycling.

In the current program (see fig. 21), a laser interferometer was used to measure the thermal contraction and/or expansion of candidate filler materials over the temperature range (+150°F to -275°F). This laser technique is a noncontact system which permits high accuracy measurements of both the absolute expansion of the filler material itself and the relative expansion between the filler material and the structural metals.

Carbon-modified epoxies have emerged as the most promising filler materials due to the low expansion coefficient of carbon. Carbon powders (in the form of 100 micron carbon spheres) have lowered the expansion of epoxies to the range of metals, while at the same time improves the thermal conductivity. Also, the carbon-modified epoxies do not appear to be susceptible to low temperature embrittlement and carbon makes epoxies easier to hand work and remove compared to metal filled epoxies.

To date an excellent match for 6061-T6 aluminum alloy has been found using EA-9309 epoxy plus carbon in a ratio of 2:1 (2 parts epoxy plus 1 part carbon) by weight. Higher carbon ratios offered no significant reduction in thermal expansion coefficient and should not be used because of potential bond strength reductions.

The carbon modified epoxies when sanded smooth, produce finishes of 50 to 80 rms compared to 30 to 40 rms for the metal filled epoxies. The surface finish of the carbon/epoxy can be improved by coating the surface of the sanded resin with lacquer glazing compound. This coating dries quickly (approximately 5 minutes) and can be readily sanded and hand rubbed to a 15 to 20 rms finish. Cryo cycling of test plates using epoxy/carbon fillers with lacquer finishes have shown no deterioration of the surface quality.

A 5-minute epoxy (modified in the same fashion as the structural adhesives) has been included in the testing program. The modified epoxy (Hardman "Extra Fast Setting")* with carbon additions, appears to be most suitable for application to fastener holes requiring frequent removal. Care should be exercised to avoid usage of this system on critical aerodynamic surfaces as the contraction differential between the system and the parent metal will cause surface dimpling.

A room temperature curing polyimide adhesive ("Super Metal")* was also studied. The Super Metal adhesive contains iron and talc particles as fillers, and has an advertised thermal expansion coefficient nearly matching that of the aluminum alloys. The adhesive was tested with and without the addition of carbon spheres. Super Metal matches aluminum alloys without modification and with only modest additions of carbon should be suitable for most cryogenic wind tunnel model applications. However, more testing will be done before carbon-modified Super Metal is used for NTF models.

3.5 Soldering

Solders have been used in conventional wind tunnel models for component and instrumentation attachment and for filling of orifice tube routing grooves and surface flaws. Use of solders on cryogenic wind tunnel models is attractive because of the thermal conductivity compatibility with parent materials, good bonding strength, and low temperature (< 600°F) application.

Generally, solders selected for conventional wind tunnel models are high in tin content as tin enhances wettability and strength. Unfortunately, low temperature usage of high tin solders could lead to joint failure due to two factors: (1) Low temperatures trigger an allotropic transformation of the familiar "white tin" to a "gray tin" powder and (2) tin and tin alloys suffer low temperature embrittlement. These problems have led to a test program to characterize the properties of solders and to determine their suitability for usage on cryogenic wind-tunnel models.

A solder consisting of 95 percent tin and 5 percent silver, which had been previously recommended for cryogenic applications (ref. 22) has now been identified as being susceptible to the "gray tin" transformation. A potential replacement for this alloy is a widely used solder consisting of 95 percent tin and 5 percent antimony. The antimony is recognized as a retardant to the formation of "gray tin" (ref. 23). Testing will be conducted on this alloy to establish its usage limitations.

Other solder alloys being characterized as to suitability and cryogenic mechanical properties include 50 percent tin - 49.5 percent lead - 0.5 percent antimony, 37.5 percent tin - 37.5 percent lead - 25 percent indium, and 50 percent lead - 50 percent indium alloys. Lead and indium have a face-centered cubic crystalline structure which remains ductile at temperatures below those imposed on models by the NTF.

3.6 Brazing

Both silver and diffusion brazing were investigated in the design study of reference 1. As pointed out in the reference, the major problems associated with model construction and high temperature brazing are (1) exposure of material to high temperatures which may cause warpage and/or change in microstructure; (2) machining and/or welding after brazing; and (3) heat treatment processing. In an attempt to avoid these kind of problems, a feasibility study was carried out (ref. 1) on the use of diffusion brazing for mechanical joining of parts. In this application for 18 Ni 200 grade maraging steel, lap shear coupons were tested. Aluminum foil was sandwiched between plates and subjected to elevated temperatures up to 900°F (below the aged heat treat for the material). The study was inconclusive.

At LaRC, the 300 series pressure tubes and Nitronic 40 plugs were successfully brazed with the Nitronic 40 wing material for the NTF Pathfinder I model. The braze alloy used was Gold-Ni (82 percent Au, 18 percent Ni) which has a melting point of 1750°F which is below the heat treat temperature for the material. Additionally proof-of-concept studies were carried out at LaRC on two wing spar specimens in which 300 series tubes were brazed into grooves to simulate tube installation in the Pathfinder II model. (See fig. 22.) The wing spar specimens were stressed up to 80 ksi in bending at temperatures approaching -300°F for approximately 5000 cycles each without detrimental effects.

More recently, problems wre encountered at LaRC in brazing 300 series stainless steel tubes into holes drilled in 18 Ni 200 grade maraging steel for the X-29A model instrumented wing. The initial approach was to select a braze material

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* Use of trademarks or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

which could be used at or slightly above the solution annealed heat treat temperature (1500°F) in order to avoid potential grain growth and degration of mechanical properties. Braze alloys tried were 58 Ag 32 Cu 10 Pd, 75 Au 20 Cu 5 Ag, and 56 Ag 42 Cu 2 Ni. Problems were encountered in that 100 percent leak proof joints could not be achieved. Both wire and powder braze material were used either alone or in combinations. Problems encountered were poor wettability, lack of flow, voids, etc. These problems revealed the sensitivity of the brazing operation to processing (cleaning, etc.) as well as reaction between the braze alloy and the 18 Ni Grade 200 material for this type of application. Finally, the Gold-ni braze material alloy used for Pathfinder I was determined to be acceptable for this application via specimen testing which utilized the wire in combination with powder braze material. The problem, however, is that the braze cycle exposes the material to 1800°F for a short time duration, and is in the temperature range that can trigger grain growth in the material which should be avoided. However, the determination was made to employ this braze material based on observing changes in grain size, running charpy specimens through the braze cycle, evaluating the design for potential loss in toughness via a fracture mechanics analysis, and making the determination that mechanical properties could be recovered through the process of grain refinement.

The results of experience to date in brazing applications indicate that the process will be highly dependent on braze material selection, preparation, and thermal management for each type of application and material, and warrants process development and/or proof-of-concept testing.

4.0 Conclusions

Design Criteria for NTF models along with the results of metallic materials characterization, grain refinement for toughness enhancement, new steel alloy development and filler and solder materials research have been reviewed. The principal conclusions to be taken from the experience at LaRC are as follows:

1. Design Criteria must provide the flexibility for designing to low safety factors without compromising structural integrity.

2. NTF models have been designed to the new criteria and successfully tested.

3. More in-depth design analysis and stringent material non-destructive examination standards are required for NTF models.

4. Fatigue and fracture toughness test programs being conducted at LaRC will establish the mechanical properties data base for primary steel alloys being used for NTF models.

5. .xtension material properties investigations show Nitronic 40 and A-286 stainless steel to be a highly acceptable stainless steel for NTF application.

6. 18 Ni Grade 200 Maraging Steel is found to be marginal with respect to fracture toughness criteria but highly desirable because of high-strength, dimensional stability, and manufacturability. All NTF balances are made from this material as well as many NTF models and stings.

7. Grain refinement is found to be both effective and feasible for improving fracture toughness properties in high strength commercially available steel alloys. A highly beneficial side effect of grain refinement is improved machinability.

8. A new 12 percent Ni alloy having exceptionally high fracture toughness, and excellent strength properties has been successfully manufactured. Both an aluminum and Titanium alloy were manufactured in plate stock. Additional work is underway to evaluate machinability and dimensional stability characteristics for the material(s).

9. Several acceptable filler materials for use in NTF model construction have been identified. The particular choice of fillers is highly dependent upon the application. Further work is being done to provide better surface finishes over filled areas which are aerodynamically critical.

10. Acceptable low temperature and high temperature solders continue to be a problem. Only one low temperature solder is considered acceptable at this time. A number of high temperature solder (braze) alloys have been studied and found to be highly process dependent for use with different metallic materials.

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TABLE 1

NTF MODEL SYSTEMS DESIGN CRITERIA SUMMARY

DESIGN ELEMENT	REQUIREMENT
STRENGTH (STRESS)	
Method 1	Compound Stress (Axial plus Bending)
	• $S_a < S_y/3$ or $S_{ult}/4$ whichever is smaller
	Shear
	• $\tau_a < S_y/6$
Method 2	Membrane
	• $S_{m_a} = F_1\ S_y/2$ where $F_1 = 0.8\ [2 - S_y/S_{ult}]$
	• Austentic and Nickel Alloys $S_{m_a} < 2/3\ S_y$ or $1/3\ S_{ult}$ whichever is smaller
	Bending
	$S_{B_a} = 1\text{-}1/2\ S_{m_a}$
	Shear
	$\tau_a < 1/2\ S_{m_a}$ or $1/2\ S_{B_a}$ (Based on yield)
	Thermal
	Algebraically added to Mechanical
	Combined (Mechanical plus Thermal)
	Shear: $\tau_a < 0.4\ S_{yield}$
	Normal: $S_a < S_{yield}$
FATIGUE	(1) - Construct Goodman Diagram which reflects reduction in fatigue strength by a factor of 2, use for allowable cyclic stress.
	or use
	(2) - Calculate cyclic stress from fixed displacement cyclic strain data, by applying safety factor of 2 on fatigue strength (stress or strain) or 20 on cycles - whichever gives most conservative results.
	- In all cases fatigue reduction factors are to be applied, (e.g., stress conc., surface finish, etc.)

Note: Material strength and stiffness properties at test temperature may be used.

TABLE 1 - CONTINUED

NTF MODEL SYSTEMS DESIGN CRITERIA SUMMARY

DESIGN ELEMENT	REQUIREMENT
FRACTURE	K_{Ic} = 85 ksi-in$^{1/2}$

* C_{V_N} (ft-lbs.)

Minimum Tensile Strength	Average (3 Specimens)	Minimum
< 65 ksi	13	10
65 - 75 ksi	15	12
75 - 95 ksi	20	15
> 95 ksi	25	20

Aluminum Alloys, Copper and its Alloys, and Nickel and its alloys - No Requirement.

- Perform Fracture Mechanics Analysis
  - Determine Screening Flaw Size
  - Predict Life

STABILITY

- Aeroelastic Stability
  - Safety Factor of 2 Against Divergence and Flutter (Based on Test Dynamic Pressure)
- Buckling

  $S_{allow} \leq 1/2\ S_{buckling}$

* C_{V_N} used primarily for selecting acceptable metallic alloys. Can be used if K_{Ic} data not available.

Symbols

S	Normal stress
τ	Shear stress

Subscripts

a	Allowable
B	Bending
m	Membrane
y	Yield
ult	Ultimate

Table 2 Young's modulus for 18 Ni 200 grade maraging steel

Temperature °F	Young's Modulus 10^6 psi
Room	26.29
-100	26.79
-200	27.24
-250	27.35

Table 3 Trends in 18 Ni 200 grade maraging steel tensile properties

Condition	Temp. °F	Yield Strength, ksi	Ult. Strength ksi
As-Received	Room	200	205
Grain Refined	Room	215	220
As-Received	-275	265	270

Table 4 Developmental Fe-12 Ni alloy compositions

Alloy Designation	Fe-12Ni-.2Ti-.05C	Fe-12Ni-.5A
Metallic Elements	Percent by Weight	Percent by Weight
Nickel	12.0 - 13.0	12.0 - 13.0
Silicon	0.010 max	0.010 max
Chromium	0.025 max	0.025 max
Titanium	0.17 - 0.26	----
Aluminum	----	0.25 - 0.50
Iron	Balance	Balance
Nonmetallic Elements	Parts Per Million by Weight	Parts Per Million by Weight
Carbon	400 - 600	100 - 500
Nitrogen	50 max	50 max
Oxygen	100 max	100 max
Phosphorus	50 max	50 max
Sulfur	50 max	50 max

Note: All other elements shall not exceed 60 ppm by weight.

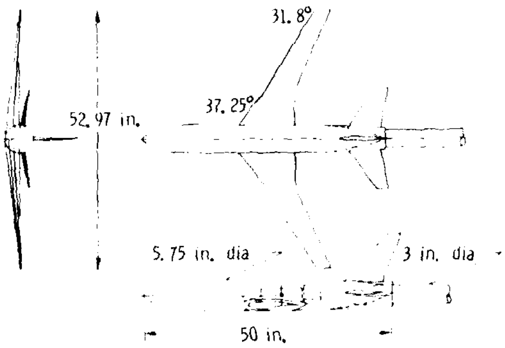

Fig. 1 Pathfinder I.

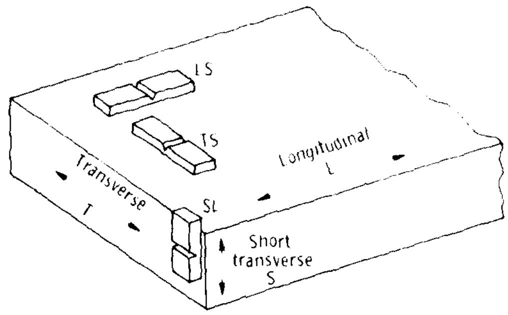

Fig. 4 Specimen orientation in plate stock material.

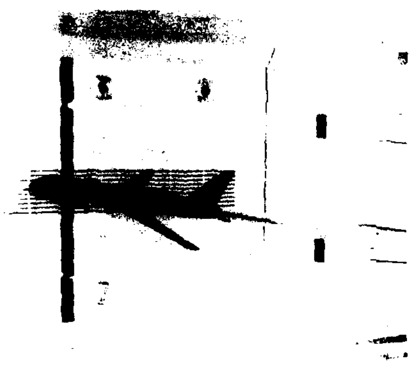

Fig. 2 Pathfinder I installed in the National Transonic Facility.

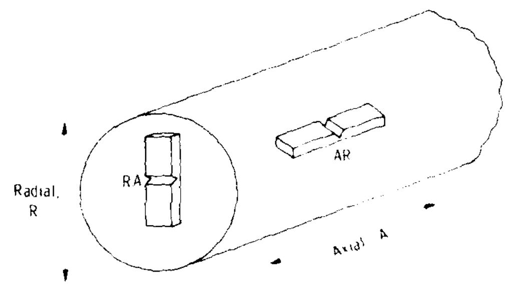

Fig. 5 Specimen orientation in bar stock material.

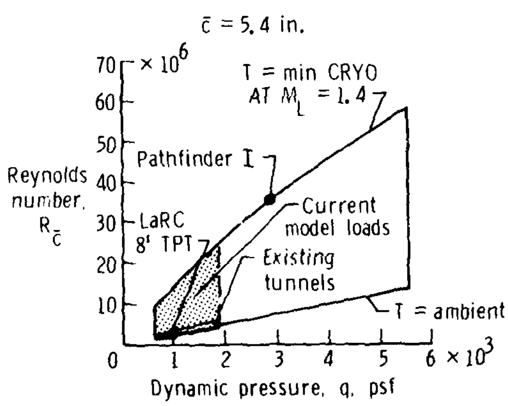

Fig. 3 NTF operating envelope at M = 0.8.

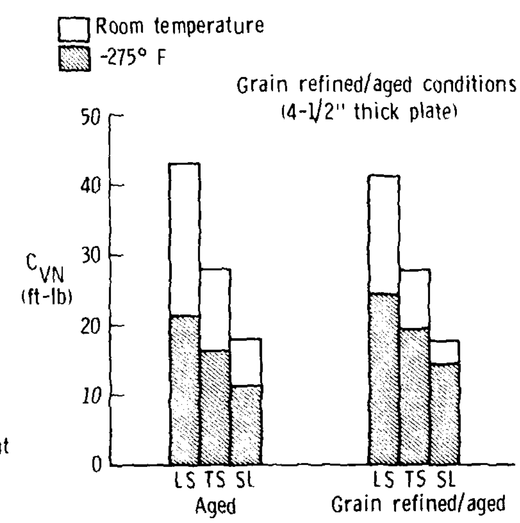

Fig. 6 Charpy V-notch data for 18 Ni 200 grade maraging steel.

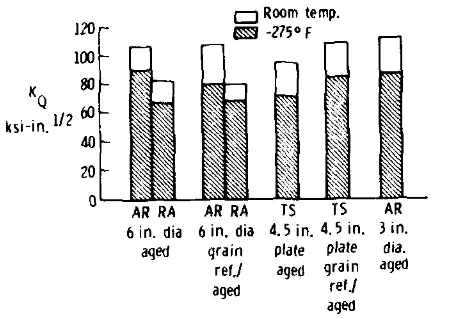

Fig. 7 Fracture toughness of 18 nickel 200 grade maraging steel at room and cryogenic temperatures.

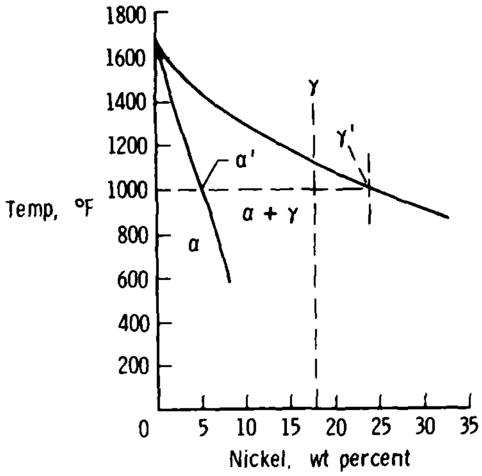

Fig. 10 Iron-nickel equilibrium diagram.

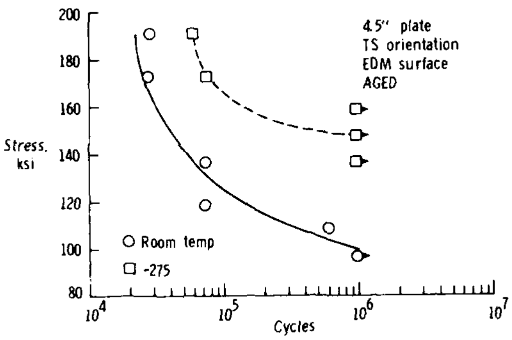

Fig. 8 Fatigue strength of 18 Ni 200 grade.

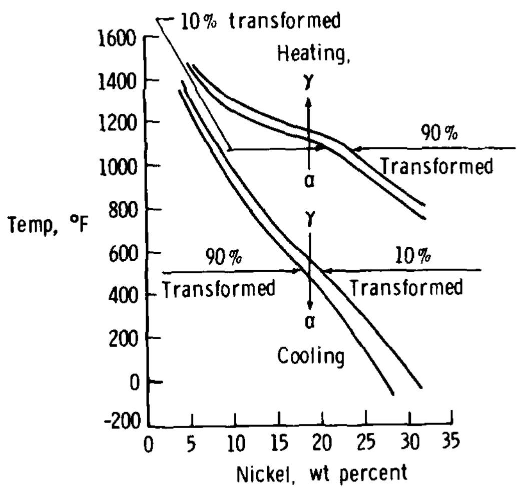

Fig. 11 Iron-nickel transformation diagram.

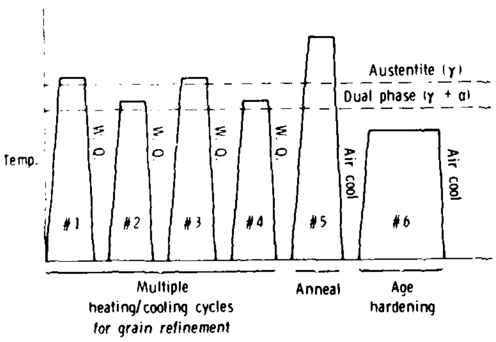

Fig. 9 Typical grain-refining heat treatment.

Fig. 12 Microstructure of HP 9-4-20.

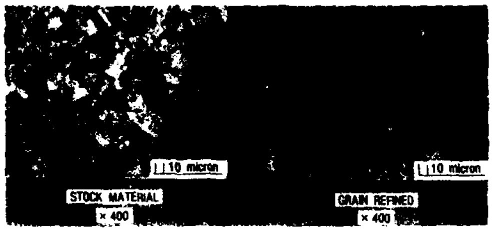

Fig. 13 Microstructure of 18 Ni 200 grade.

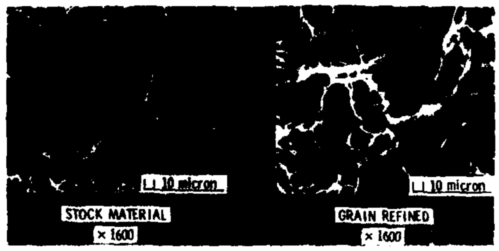

Fig. 16 Fracture surface of grain refined 18 Ni 200 grade at -320°F.

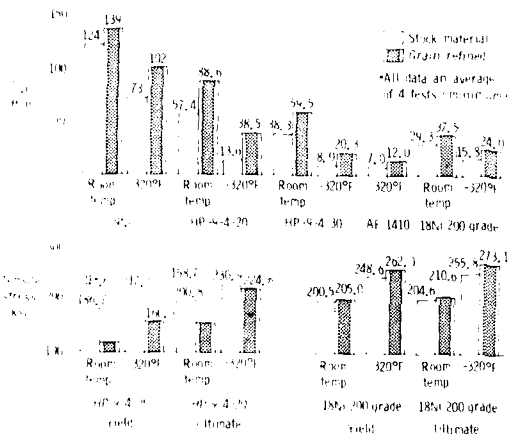

Fig. 14 Effect of grain refinement on mechanical properties.

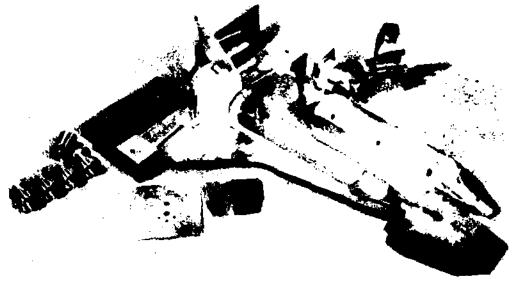

Fig. 17 .01 Scale Shuttle Model illustrating grain refined fuselage/wing section.

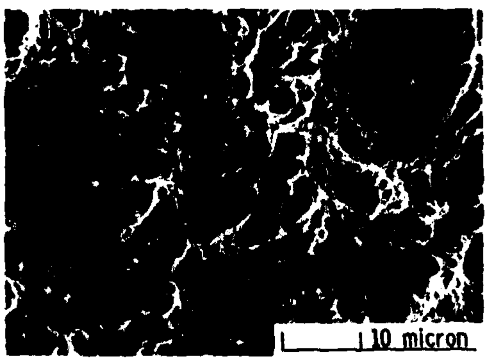

Fig. 15 Fracture surface of grain refined HP 9-4-20 at -320°F.

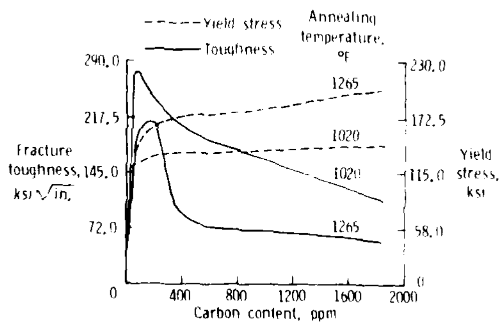

Fig. 18 Effect of carbon content on fracture toughness and yield stress of Fe-12Ni-0.5Al alloy at -320°F.

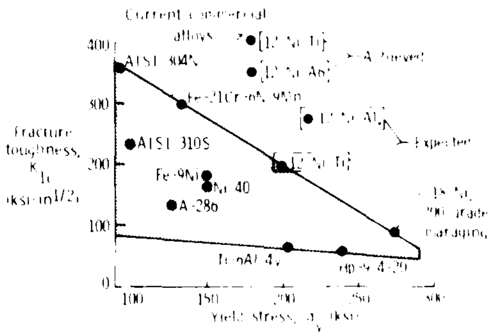

Fig. 19 Comparison of fracture toughness and yield stress of Fe-12Ni experimental alloys with commercial alloys at -320 F.

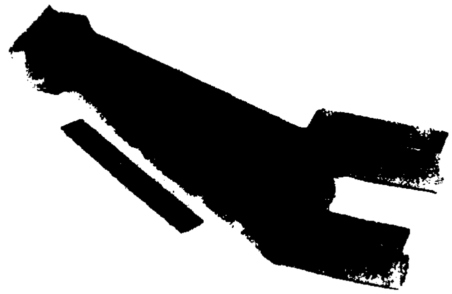

Fig. 22 Wing Spar Soldering and Brazing Proof-of-concept specimen.

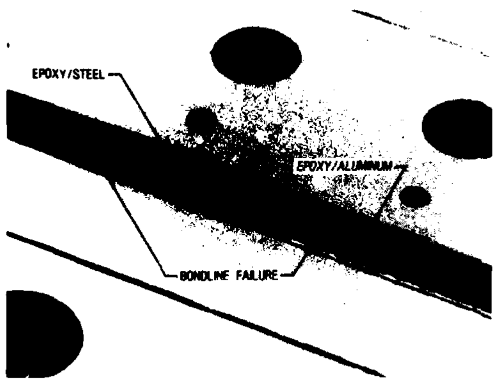

Fig. 20 Failure caused by thermal expansion mismatch between aluminum test plate and metal filled epoxies.

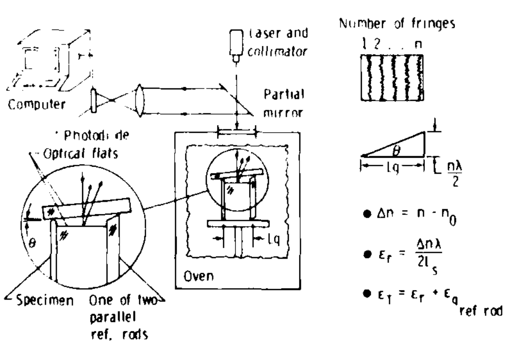

Fig. 21 Priest interferometer.

Design and Construction of Models for the National Transonic Facility - II

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Summary

This lecture presents the results of fastener load and retention systems tests which were carried out as a part of the cryogenic models technology development program at the NASA Langley Research Center (LaRC). Various design concepts for the National Transonic Facility (NTF) developmental and production models are discussed. A number of NTF models are described with emphasis on materials used, uniqueness of design and design drivers. Design and fabrication experience is presented in terms of the primary thermal and mechanical considerations required for design as well as fabrication. Cost considerations are addressed in terms of factors influencing costs for NTF models and cost data comparisons which are taken from both NASA Langley and industry experience.

1.0 Introduction

Full utilization of the high Reynolds number provided by the NTF requires the extension of the state-of-the-art in model design and fabrication. Designers are faced with the challenge of developing new design concepts for many models to be tested in the NTF. Inherent in this process is the need for proof-of-concept studies for design verification. A major challenge lies in the area of designing the model so as to minimize the fabrication costs where possible, even when faced with the more stringent tolerance and surface finish requirements.

Much has been learned at the NASA Langley Research Center over the past few years with regard to design methodology, fabrication problems, and proof-of-concept studies.[1] The purpose of this lecture is to report on fastener load and fastener retention systems tests carried out at the LaRC. Also, various design concepts for NTF models are presented with particular emphasis on design problems associated with instrumented wings and flap attachments. Design and Fabrication Experience with NTF models is presented and cost factors for NTF models as compared to conventional models are presented, based on the most current information available.

2.0 Fastener Load Tests and Retention Systems Tests

Although fastener strength and retention should always be primary considerations in the design of wind-tunnel models, these factors become even more critical for high-Reynolds-number testing at cryogenic temperatures and load conditions such as those which may be imposed on NTF model systems. The looseness, loss, or failure of a fastener could lead to structural component failures, which, in turn, could result in wind tunnel damage. For these reasons, test programs[2] were initiated at LaRC to investigate fasteners and fastener retention systems for use in NTF models.

2.1 Load Tests

A large number of special screws made of standard A-286 stainless steel were purchased for use in models to be tested at cryogenic temperatures in the NTF. Since load data for these screws at cryogenic temperatures were not available, it was necessary to determine the tensile load capability and failure mode of the screws at both cryogenic and room temperature. Nine sizes and three types of screws were tested as listed in table 1. The only data supplied by the manufacturer are given in table 2. The failure load(s) given in table 2 were based on room temperature tests for only one screw of each size. As purchased, the 10-32 and 1/4-28 screws were threaded for only 1 inch for screw lengths of 1.5 in. and 3.0 in. In use, many of these screws will require threads all the way to the head. Therefore, ten of each of these screws were modified by continuing the threads to the head and were included in the test program.

The program consisted of applying a tensile load, to failure, to five of each size and type of screw at room temperature and at cryogenic temperature (-275°F). The screws were tested in an Instron model 1115 universal tester. A special set of fixtures was designed and fabricated to fit the Instron to match all the sizes and types of screws. A typical setup is shown in figure 1. Five of each type and size screw were broken at room temperature with a strip chart recording the load and head movement versus time. Visual observations of each break were noted on the strip chart. Five of each type and size screw were then broken at cryogenic temperature with the same data collected. For the cryogenic tests, the environmental chamber on the Instron

was cooled to -275°F and each screw setup was allowed to soak for approximately 45-60 minutes to obtain a uniform temperature throughout the setup.

The strip chart recordings were used to determine the yield load, the ultimate load, and the elongation of each screw. Tables 3 and 4 give the summarized results at room temperature and cryo temperature respectively. Presented for each size and type of screw are the minimum yield load (determined by .2 percent offset in the elongation), the minimum ultimate load obtained, and the number of failures at the head and in the threads.

Principal observations on the failure modes of the screws tested were: (1) Heads popped off all of the 1-72 button head screws at both room temperature and cryo temperatures; (2) All socket cap screw failures occurred in the threads; (3) None of the #2, 6, 8, and 1/4" socket flat head screws had any head failures at room temperature; (4) At cryo temperature, the #6, 8, 1/4" and 1/4" modified socket flat head screws did not have any head failures; and (5) Generally, head failures occurred at lower loads than thread failures for a given screw size and type and fractured through the bottom of the socket.

Caution should be used in any attempt to calculate stresses in these screws. The minimum loads listed for most of the socket flat head screws are values for a head failure where the exact cross-sectional area is unknown. The data provided in tables 3 and 4 are currently being used to design screws for NTF models at LaRC. As a conservative measure, minimum values were chosen as opposed to using average values. Interestingly enough, the room temperature ultimate (failure) loads do not correlate very well with data supplied by the manufacturer, with the manufacturer supplied failure loads generally being less for the smaller screws and greater for the larger (greater than 6-32) screws.

2.2 Retention Systems

A comprehensive test program was conducted to examine the effectiveness of various fastener locking systems for cryogenic applications. Five locking systems were tested using the special A-286 screws and the primary metallic alloys that are being used for NTF models. The locking system effectiveness was examined by simple no load cycling to cryogenic temperatures (-275°F) as well as with dynamic and static loading at cryogenic temperatures.

Five locking systems (see fig. 2) were tested. These include self-locking Heli-coils, "Spiralock" *Threadform*, "Loctite," "Crest," and epoxy over screw heads.* In addition, tests were performed on screws without any locking device in order to establish a baseline for judging the effectiveness of locking systems. Screw sizes chosen were 1/4-28 socket head cap screws, and 2-56 flat head socket cap screws which are believed to be representative of the largest and smallest screws that will be used in typical model construction.

Test specimen assemblies are illustrated in figures 3(a) through 3(c) and figure 4, and are scaled to be representative of a conventional joint attachment on models. Two basic assemblies were used for tests. Five 1/4-28 screws were used in one type of the specimen assemblies while nine 2-56 screws were used in the other type. A specially designed torque wrench was used to give accurate torque values at both the tightened and breakaway values. The screws were initially preloaded to approximately one fourth of the ultimate strength through the use of a nomograph relating torque values for each size screw tested.

The locking systems were initially tested in a no-load condition by measuring breakaway torque before cryo cycling, after 1 and 5 cycles, and at -275°F as indicated in tables 5 and 6. The data given in tables 5 and 6 for the no load conditions (cryo cycling only) are averaged values for all screws in each test specimen except for the control screw. In addition, static (bending) loads calculated to load the screws up to the preload value were applied to the specimen at equilibrium cryogenic temperatures. (See fig. 5.) Ten load cycles were completed for each specimen, they were then removed from the test fixture, and breakaway torque values were measured at room temperature.

Dynamic load tests were conducted in which the test specimens were mounted on a bakelite block and attached to a shaker table as shown in figure 6. LN_2 was pumped through the test piece to maintain the specimen at cryogenic temperature, while the specimen was subjected to a 30-minute random vibration environment over a frequency range of 20-200 Hz at 9 g rms to simulate severe load conditions that a model might possibly experience in the NTF. Again breakaway torques were measured after the vibration test and at room temperature. It should be noted that the data given in tables 5 and 6 for the static and dynamic load tests are averaged values for all screws in the test piece. For the dynamic and static loads tests there was no control screw.

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* Use of trademarks or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

A graphical representation of the averaged test data for self-locking Heli-coils used with 1/4-28 screws for each of the specimen materials is given in figure 7.

General conclusions from the test program were as follows:

(1) The cryo cycling in the absence of mechanical loads produced a decrease in breakaway torque for all systems tested.

(2) The self-locking Heli-coil is an effective and convenient device to work with for larger screws and for all materials studied. However, the use of this device for small screws is questionable due to problems encountered with the screw locking in the Heli-coil.

(3) The Spiralock threadform is a simple and effective device for both sizes of screws and seem to be least affected by the cryogenic environment. Overall, this may be the best locking system for cryogenic applications, partic.larly with small screws.

(4) Loctite, although very effective at retaining the screws was not an easy system to use. Initial assembly was not difficult, which required spraying a primer on, applying the Loctite and then assembly. However, subsequent use of the same parts required a tap to be run through the tapped hole and a die nut to be run over the threads to prevent plastic material build-up.

(5) Crest was found to be similar to Loctite, a very effective locking device but cleaning for reuse is required. A major problem is the 72-hour cure time which would eliminate Crest for use with model changes to be made in the tunnel.

(6) The aluminum filled epoxy applied over and around the screw heads was effective but did not have the higher break away torque found with the Loctite and Crest.

In general all systems, were found to be effective locking devices. Also tests at -275°F imply that the cold temperatures acts to help screw retention, which is likely due to differential thermal contraction and/or increased friction (thread binding) effects. Similar findings are reported in reference 3.

3.0 Design Concepts for NTF Models

The design of NTF models becomes more complicated in that more conventional (non-cryogenic) design methodology may not work because of potentially high loads, cryogenic test environment and more stringent tolerances and surface finishes. This is particularly true for instrumented wings and control surface attachments. Various designs are reported on in references 3 through 6. For example, the Pathfinder I (ref. 4) utilized a two-piece tongue-in-groove wing design which proved to be quite successful. Also more conventional instrumented wing designs have also been employed for NTF models. Examples include conventional cover plate designs such as those used for the models in reference 1 and the Lockheed wing (see ref. 7) to be tested on Pathfinder I, and the Boeing 767 model which utilizes surface routing of tubes in grooves covered with filler material.

The more difficult designs involve very thin, low aspect ratio instrumented wings. A good example is the Pathfinder II which is a developmental model chosen to address highly loaded thin wing design problems and provide for interchangeability of lifting surfaces, flaps, etc., and is described in the following sections.

3.1 Pathfinder II Design Features

The NTF Pathfinder II model (figures 8 and 9) is a high performance fighter configuration that is designed to serve as a "Generic" model. The model is designed around a cylindrical strongback to which the aerodynamic shape is connected. The noise and aft section are mounted to the strongback and retained by specially designed screw dowels. The mid-section of the model is made up of four equal sections that provide for interchange of the wing and adjustment of the area distribution by changing the shape of the canopy and belly sections. The model wing is a thin, highly twisted supercritical airfoil shape with interchangeable leading and trailing edge flaps. The thinness of the wing at the trailing edge flap hinge line coupled with the high aerodynamic loads precluded the use of a conventional lap or tongue and groove joint. A special int was designed for the trailing edge flap. (See figure 9.) This "Alternating Surface Segmented Lap Joint" eliminates the need for shear pins and reduces the tensile load in the attachment screws. The joint consists of a system of tabs on the flap that mesh with grooves in the wing spar. The number, size, and location of the tabs were developed from a detailed finite element analysis of the wing flap system. This type joint has an added advantage that because of the sweep of the wing, the flap tabs are forced into the wing groove, i.e., should the screws come loose the flap will not detach from the wing spar. The leading edge flaps utilize a conventional lap joint design. A proof-of-concept test specimen of the trailing edge attachment is shown in figures 10 and 11.

3.2 Design Concepts for the Thin, Highly Twisted Pressure Wings for Pathfinder II

The Pathfinder II has been designed with very thin, highly twisted and cambered wings. These characteristics represent a major design challenge when dealing with the attachment of flap elements. The design is further complicated by the high loads and cryogenic temperatures imposed on models in the NTF which cause problems with the conventional installation of pressure tubes due to induced aerodynamic distortions over the surface routed pressure tubes. All of these considerations combine to make conventional design techniques questionable for NTF models with very thin, highly loaded wings. In an attempt to solve these problems, LaRC investigated several alternative design techniques.

Three design concepts were studied for the Pathfinder II instrumented wing. These concepts are (1) surface routing of tubes soldered or brazed in the wing, (2) nickel plating over tubes routed in the wing spar depicted in fig. 12 and (3) fiberglass overwrap of the wing spar after tube routing.

The surface routing of tubes without plating or overwrap has been selected for the Pathfinder II wing. In this design, the tubes are soldered or brazed in place after machining to contour. The solder areas are then smoothed prior to drilling of orifices. This concept was adopted based on proof-of concept specimen testing to establish confidence that the more conventional method would work. However, the grooves have to be machined to very close tolerance for placement of tubes near the final machined surface for the solder or braze operation. In order to verify the machining accuracy and setup, proof-of-concept machined specimens will be done to verify that the wing can be final machined without a high risk of machining into the tubes in the very thin highly curved regions.

In the other two concepts, the nickel plating and epoxy E-Glass are used as a means of providing a material covering over the wing spar. Both the nickel plating process and fiberglass overwrap were installed oversize and machined to the specified contour. The fiberglass overwrap concept is illustrated in figures 13 and 14 which show the grooved wing spar and fiberglass overwrap after tube installation.

The fiberglass overwrap concept looks very promising at this time, particularly in view of potential ease of fabrication. This particular specimen was fabricated at considerably less cost than the nickel plated specimen. Also, it was found that surface finish, tolerance, and orifice quality could be achieved for the fiberglass surface. In the case of the nickel plating process, an added advantage is that of obtaining mechanical properties in the plating material comparable to the spar material, as well as achieving the required surface finish and tolerance.

Preliminary fatigue testing (see fig. 15) of both the fiberglass and nickel plating concepts at cryogenic temperatures have produced encouraging results with no major problems encountered to date. Extensive testing of these concepts is planned for the future to further refine the fabrication processes and to further evaluate the design adequacy at cryo temperatures.

4.0 Design and Fabrication Experience for NTF Models

Extensive in-house experience has been obtained in the design and fabrication of model systems for testing at cryogenic temperatures in the NTF. Models of representative wide body transports (Pathfinder I and 1/2-Scale Pathfinder I), see figure 16, Space Shuttle Orbiter, figures 17 and 18, and Axisymmetric Bodies, figure 19 are ready for tunnel entry. The Pathfinder I model was subjected to approximately 25 hours of testing over the planned test envelope in December 1984 and January 1985. The previously mentioned high performance fighter configuration (Pathfinder II) has been designed and is being fabricated. All of the currently available and cryogenically acceptable model metallic materials (Nitronic 40, Nitronic 60, PH 13-8 Mo condition H1150M, and A-286 stainless steels; 18 Ni 200 Grade maraging steel; and 6061 Aluminum) are used in the various aforementioned models.

There are two major differences in designing models for the NTF as compared to designing models for testing in conventional wind tunnels. The first of these is the cryogenic environment with temperatures possibly as low as -320°F, and secondly, in order to utilize the full capability of the NTF for testing at high Reynolds number, many of the models will have to be designed for testing at dynamic pressures considerably greater than those which can be achieved in most transonic tunnels. To date, the high loads requirements on the model components has had a greater impact on the model design than the cryogenic environment.

4.1 Mechanical Design

The basic approach in developing the mechanical design of the aforementioned NTF models was to minimize the number of structural joints in order to reduce the effects of temperature gradients in model components. Additionally, these design concepts provide for convenient testing of models in any configuration such as fuselage only, fuselage and wing, or complete configuration. Where possible and practical,

similar materials have been used but dissimilar materials can be utilized as demonstrated by the Shuttle design (fig. 17) which employs an 18 Ni 200 Grade fuselage, Nitronic 60 drive system components, and A-286 stainless steel for all other structural components.

It appears that in most cases, conventional mechanical design methodology can be used. One of the principal load problem areas, however, is in the design of attachment joints, particularly for very thin airfoil sections. This subject was addressed in the previous section.

The utilization of higher strength properties at cryogenic temperature for metallic alloys coupled with the advantage of being able to use lower safety factors (requiring additional engineering analyses) will provide for better utilization of the facility. However, the model overall test envelope at a given dynamic pressure could be impacted in some cases because the ambient temperature strength properties can be considerably lower than at cryogenic temperatures for some materials such as the stainless steels. It seems that in most cases the model system dynamic pressure capability will be governed by divergence or balance limitations rather than strength.

4.2 Thermal Design

Generally, the basic thermal design practices for models to be tested at elevated temperatures also apply to cryogenic model except that differential contraction due to cold temperatures must be accounted for instead of expansion due to heating. The electronic instrumentation and electric motors used in conventional models may be used in cryogenic models if they are located in a temperature controlled package. For example, the same actuating system (electric motors, potentiometers and drive system) used in a .02 scale Space Shuttle Orbiter model (see ref. 8) is used in the NTF Orbiter model shown in figure 18. The motors and potentiometers will be heated.

It has been found from both design and analysis experience that thermal design criteria (see for example, the test section cooldown, post-model maintenance cooldown and warm-up criteria, figures 20, 21, and 22, respectively) have not been major drivers on the design.[9] Also, the analysis efforts required to verify adequacy of the thermal design have not been as extensive as originally envisioned. In general, good thermal design practice allowing for problems associated with thermal mismatch has been sufficient. The tunnel capability of approximately ±86°F step change in temperature at test point as indicated in figure 20 has been found to be the most severe thermal load case for most models. In addition, the post-model maintenance cooldown criteria, (fig. 21) which in some cases may be significant, is the rapid temperature change associated with the post-model maintenance cooldown. However, the transient occurs at very low convection rates (no aerodynamic flow) and in the absence of mechanical loads.

Also, it should be noted that the present operational test procedures call for the model to be brought to zero angle of attack until thermal equilibrium is reached. This alleviates having to add potentially high mechanical (aerodynamic) loads to potentially high thermal loads during testing. Typically, temperature gradients in models do not produce thermal stresses large enough to be a problem unless the area sustaining the gradient connects two separate components through pins and/or fasteners. Relative movement between components (e.g., flaps and wing) can give rise to high stress in the fasteners, since the fasteners act as constraints and transfer the resulting loads at the fastener locations. Because very small relative motions can give rise to very high shear loads in screws, proof-of-concept studies were performed to evaluate thermal load behavior for a representative lap joint figure 23, and the alternating segmented lap joint previously discussed (fig. 10). In the case of the simple lap joint specimen, failure of the screws could not be effected by immersion into liquid nitrogen even though analyses indicated that the screws should fail in shear. It is believed that because of the very small relative displacements, and less than precise (tight) tolerances on the screws and screw holes, the theoretical loads are not developed in the fasteners. This finding points out the possible fallacy of analyses based on idealized conditions, and is important since design of attachments can be largely driven by thermal loads. Further work is being done with the proof-of-concept specimens to better understand the mechanism of typical attachment fasteners behavior under thermal load.

5.0 Cost Considerations

The potential for a significant increase in model costs for NTF has been of concern from the beginning and for a number of reasons. It is recognized that current aerodynamic and design criteria requirements will impact both the engineering design and fabrication costs, but quantifying cost increments both present and future is still difficult. However, the Boeing experience on the 767 model as reported in reference 5 provided initial data. In this case, the comparison was made for the NTF model relative to a so-called conventional model (non-cryogenic) which gave estimated cost factors of 2 to 1 on design and 1.5 to 1 on fabrication. The Fighter Design Study as reported in reference 3 also estimates a present overall (both design and fabrication) cost increment of 2.1 to 1 decreasing to 1.5 to 1 with further R&D and experience.

At LaRC, the potential for increased costs was addressed in reference 10 but not quantified, because the developmental models designed and fabricated up to that point were front-end loaded with R&D and Proof-of-Concept testing. However, some estimates on fabrication (machining) costs for various materials can be made based on more recent LaRC experience. Estimates of cost to fabricate NTF models from various materials to a surface finish of RMS 8-10 and a ±.002 inch tolerance are given in table 7. These estimates were made by comparing the cost to fabricate and instrument a typical research model (wing, empennage, and fuselage) constructed of 17-4 PH stainless steel (a commonly used material for conventional models) to a ±.005 inch tolerance and a 32 rms surface finish. It was assumed that the 17-4 model is rough machined, heat treated, finished machined, and hand polished.

One major observation from the estimates given in table 7 is that in terms of the total fabrication cost ratio, the more stringent surface finish and tolerances add only about 10 percent to the overall machining cost ratio. The major costs being that associated with machining to contour. Of course, each model is different and it is difficult to generalize. Design is particularly important in impacting fabrication cost and should be approached with fabrication cost considerations in mind.

Currently, with the improved tooling and processing the machining costs of the cryogenic steels is projected to drop significantly. Also, as the design and analysis process evolves and the R&D and proof-of-concept work is carried out, it is anticipated that in the next few years the overall cost factor (NTF versus conventional) will be somewhere between 1.5 to 1.25 and should decrease even further with additional experience and new technology development.

6.0 Conclusions

Fastener test program results, and various design concepts utilized for NTF models are presented. The design and fabrication experience for NTF models along with cost considerations based on the most current data are presented. The primary conclusions are as follows:

(1) A data base has been developed for use by model designers in selecting type and size A-286 stainless steel screws for use in NTF models.

(2) Various fastener retention systems have been evaluated for use in NTF models. Most systems tested were found to be effective locking devices with some differences being observed with respect to ease of application, cleanup, and reuse. Cryogenic temperatures act to improve fastener retention.

(3) New design concepts are required for many NTF models in order to accommodate cryogenic temperatures and potentially high loads for testing at high Reynolds number.

(4) New as well as conventional design concepts require proof-of-concept testing. This is particularly true for highly loaded models and for components such as flap attachments and instrumented wings.

(5) A wide range of model configurations have been fabricated and are ready for testing in the NTF.

(6) Design experience has shown the major driver to be mechanical loads as opposed to thermal loads.

(7) In many cases, conventional (non-NTF) mechanical design methodology can be used, but should be supported by proof-of-concept testing.

(8) Good thermal design practice allowing for problems associated thermal mismatch has been sufficient in most cases.

(9) Model system test dynamic pressure capability will, as a rule, be governed by aeroelastic divergence or balance limitations rather than strength.

(10) Model systems can be designed and fabricated for the NTF without being cost prohibitive. While engineering costs will remain somewhat high for NTF models, machining costs will tend to approach that of non-NTF models in the near future. Overall cost factor (NTF versus conventional) will approach 1.5 to 1.25 in the next few years and is expected to decrease further with design experience and fabrication technology improvement.

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Table 1 Special A-286 Screw Sizes and Types

Size	Type
0-80	Socket flat head screw (SFHS)
1-72	Button head
2-56	SFHS and socket cap screw (SCS)
3-48	SFHS
4-40	SFHS and SCS
6-32	SFHS and SCS
8-32	SFHS and SCS
10-32	SFHS and SCS
1/4-28	SFHS and SCS

Table 2 Manufacturer supplied ultimate loads for special A-286 screws

Size	Type	Ultimate Load* at R.T., lbs.
0-80	SFHS	330
1-72	Button Head	190
2-56	SFHS	460
2-56	SCS	725
3-48	SFHS	780
4-40	SFHS	1145
4-40	SCS	1090
6-32	SFHS	1540
6-32	SCS	1500
8-32	SFHS	2480
8-32	SCS	2180
10-32	SFHS	3780
10-32	SCS	4180
1/4-28	SFHS	7080
1/4-28	SCS	6880

* Data for one screw only

Table 3 Minimum yield and ultimate loads and failure modes at room temp.

Screw	Min. Yield lb.	Min. Ult. lb.	Failures Head/Threads
0-80 SFHS	206	320	3/2
1-72 BH	370	387	5/0
2-56 SFHS	548	680	0/5
2-56 SCS	546	688	0/5
3-48 SFHS	737	840	2/3
4-40 SFHS	792	1070	2/3
4-40 SCS	932	1089	0/5
6-32 SFHS	1465	1725	0/5
6-32 SCS	1465	1678	0/5
8-32 SFHS	1952	2425	0/5
8-32 SCS	1790	2050	0/5
10-32 SFHS	3270	3825	3/2
10-32 SCS	3720	4060	0/5
10-32 SFHS(Mod)	2870	3440	2/3
10-32 SCS(Mod)	2930	3840	0/5
1/4-28 SFHS	6550	7100	0/5
1/4-28 SCS	6360	6766	0/5
1/4-28 SFHS(Mod)	5520	6335	2/3
1/4-28 SCS(Mod)	5420	6500	0/5

Table 4 Minimum yield and ultimate loads and failure modes at -275°F

Screw	Min. Yield lb.	Min. Ult. lb.	Failures Head/Threads
0-80 SFHS	355	396	1/4
1-72 BH	425	477	5/0
2-56 SFHS	596	834	1/4
2-56 SCS	655	856	0/5
3-48 SFHS	710	1079	2/3
4-40 SFHS	950	1255	4/1
4-40 SCS	1070	1341	0/5
6-32 SFHS	1700	2125	0/5
6-32 SCS	1650	2066	0/5
8-32 SFHS	2380	3045	0/5
8-32 SCS	2220	2666	0/5
10-32 SFHS	4000	4660	3/2
10-32 SCS	4400	5020	0/5
10-32 SFHS(Mod)	3400	4670	1/4
10-32 SCS(Mod)	3690	4625	0/5
1/4-28 SFHS	8090	8966	0/5
1/4-28 SCS	7390	8500	0/5
1/4-28 SFHS(Mod)	6490	7675	0/5
1/4-28 SCS(Mod)	6320	8050	0/5

Table 5 Averaged break-away torque values for special A-286 2-56 Screws with various locking devices (in-lb)

Locking Device	Before Cycling	After 1 Cycle	After 5 Cycles	At -275°F	Control Screw	Dynamic Loading	Static Loading
			A-286 Stainless Steel				
Heli-coils	2.07	1.85	1.98	2.56	2.05	2.15	*
Spiralock	1.76	1.89	1.91	3.45	1.50	2.12	1.84
Loctite 222	3.41	2.88	2.63	**	2.50	3.17	2.96
Crest	3.27	3.06	3.03	**	2.30	2.53	3.24
Epoxy	2.74	2.53	2.79	4.11	2.25	2.45	2.31
No device	2.24	2.28	2.42	3.07	2.25	1.92	1.77
			PH 13-8 Molybdenum Stainless Steel				
Heli-coils	1.94	1.42	1.44	2.16	.90	1.75	*
Spiralock	1.89	1.19	1.61	2.67	.70	1.93	1.71
Loctite 222	3.18	2.39	2.88	**	3.30	2.87	2.62
Crest	3.28	2.96	3.21	**	1.70	2.40	2.88
Epoxy	2.93	2.28	2.48	+	1.60	3.19	2.71
No device	2.22	.74	1.61	2.83	.30	1.77	1.84
			Nitronic 40 Stainless Steel				
Heli-coils	1.94	2.01	1.98	3.83	1.80	2.04	*
Spiralock	1.74	1.77	1.85	3.68	1.60	1.98	1.93
Loctite 222	2.81	2.83	2.92	*	3.20	3.51	2.76
Crest	3.14	3.13	3.58	*	2.80	2.97	3.15
Epoxy	2.49	2.68	2.34	3.75	1.70	3.14	2.47
No device	2.39	2.21	2.16	2.82	2.15	1.51	1.87
			18 Ni Grade 200				
Heli-coils	1.88	1.84	1.76	2.54	1.65	1.91	*
Spiralock	2.30	1.83	1.65	2.50	.95	1.87	1.47
Loctite 222	3.01	2.98	3.01	*	2.65	3.08	2.72
Crest	3.46	2.60	2.68	*	1.28	3.37	3.24
Epoxy	2.74	1.30	2.43	+	1.60	3.23	2.64
No device	2.16	.49	1.31	2.98	1.75	1.99	1.99
			6061 T6 Aluminum				
Heli-coils	1.75	1.81	1.90	2.58	1.95	2.18	1.78
Spiralock	1.75	1.63	1.88	2.57	1.90	2.08	1.66
Loctite 222	2.86	2.69	2.93	*	2.75	3.29	2.51
Crest	2.83	2.87	2.76	*	3.12	3.07	2.84
Epoxy	2.56	2.12	2.31	3.94	2.25	2.81	3.16
No device	1.93	1.74	1.71	2.26	1.75	2.30	2.27

* Screws too loose to read
** Screws could not be turned at this temperature
\+ Sockets in screw head were stripped

Table 6 Averaged break-away torque values for special A-286 1/4-28 Screws with various locking devices (in-lb)

Locking Device	Before Cycling	After 1 Cycle	After 5 Cycles	At -275°F	Control Screw	Dynamic Loading	Static Loading
A-286 Stainless Steel							
Heli-coils	85.0	86.0	84.0	138.3	65.0	76.0	72.6
Spiralock	94.3	72.3	88.5	112.5	70.0	78.4	66.2
Loctite 242	114.5	101.3	103.8	169.8	98.0	81.8	86.0
Crest	76.0	79.8	98.5	232.7	73.0	81.4	76.0
Epoxy	104.5	109.5	117.3	117.0	88.0	124.4	117.5
No device	78.0	81.0	71.5	143.3	72.0	78.4	72.8
PH 13-8 Molybdenum Stainless Steel							
Heli-coils	74.3	73.0	69.0	107.0	51.0	70.2	74.6
Spiralock	83.5	72.8	67.8	67.8	64.0	68.2	60.0
Loctite 242	104.8	78.8	84.8	185.8	37.0	84.2	79.4
Crest	75.0	77.0	86.5	223.0	60.0	74.4	74.6
Epoxy	112.5	125.0	124.3	117.0	89.0	128.6	111.2
No device	81.5	59.8	70.5	128.3	56.0	74.2	70.2
Nitronic 40 Stainless Steel							
Heli-coils	82.3	81.3	79.8	112.5	*	68.6	72.8
Spiralock	92.8	87.0	84.3	91.8	80.0	85.4	70.4
Loctite 242	110.8	98.5	94.0	175.8	87.0	79.0	78.0
Crest	77.8	80.8	85.8	231.0	84.0	72.4	77.2
Epoxy	115.5	120.3	117.3	109.3	107.0	113.0	116.6
No device	81.0	81.3	75.8	121.0	67.0	78.4	74.8
18 Ni Grade 200							
Heli-coils	87.0	89.5	88.8	138.8	79.0	80.8	74.2
Spiralock	90.0	83.8	81.0	93.0	85.0	73.4	69.6
Loctite 242	107.8	92.5	91.8	162.8	87.0	87.6	74.8
Crest	74.0	83.3	91.5	249.0	70.0	78.6	76.6
Epoxy	107.3	108.5	113.5	111.8	115.0	112.4	104.0
No device	83.8	84.5	67.8	136.5	71.0	80.0	74.8
6061 T6 Aluminum							
Heli-coils	79.5	76.3	77.3	94.8	72.0	75.0	67.8
Spiralock	78.8	78.0	79.3	107.0	75.0	65.4	41.4
Loctite 242	77.8	86.3	78.5	171.5	57.0	83.6	66.4
Crest	76.8	91.3	83.8	249.5	75.0	78.2	77.6
Epoxy	105.5	96.5	94.3	143.5	99.0	96.2	87.8
No device	82.3	85.0	72.3	108.5	76.0	71.8	75.2

* Screw too loose to read

Table 7 Estimated fabrication cost factors for cryogenic model materials.

Model material	Machining cost factor	Increase due to 8-10 rms finish	Increase due to ±.002 tolerance	*Total cost factor
Nitronic 40	1.50	.040	.120	1.66
A-286	1.50	.040	.120	1.66
PH 13-8 1150 M	1.25	.030	.090	1.37
18 Ni grade 200	1.00	.025	.075	1.10
18 Ni grade 200 (grain refined)	.75	.025	.075	0.85
6061 T-6 Al.	0.50	.010	.030	0.54

*Cost factor of 1.0 would correspond to a non-cryogenic model fabricated from 17-4 PH stainless steel with a 32rms finish and ±.005 tolerance

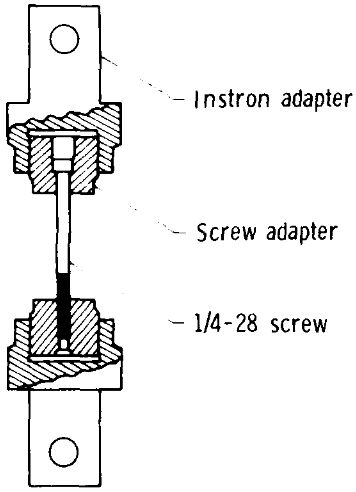
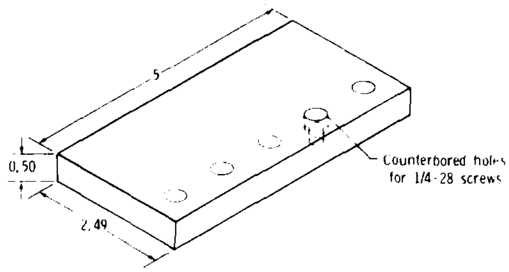
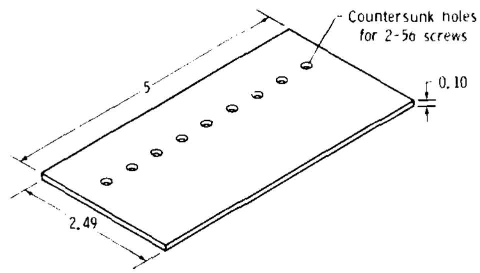


Fig. 1 Typical test setup.



(b) Specimen part A



(c) Specimen part B

Fig. 3 Concluded.

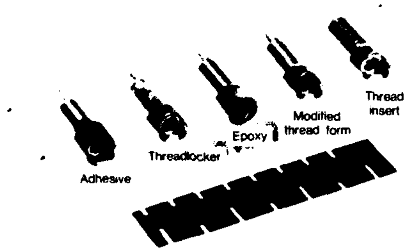


Fig. 2 Cutaway specimen showing five retention devices used with 1/4-28 screw.

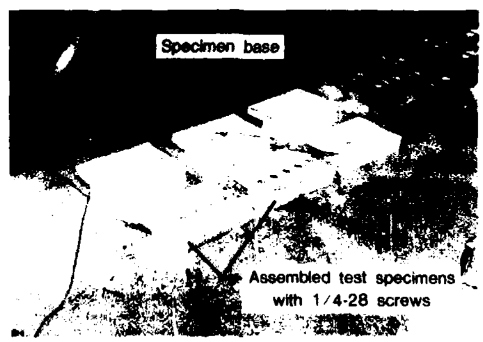
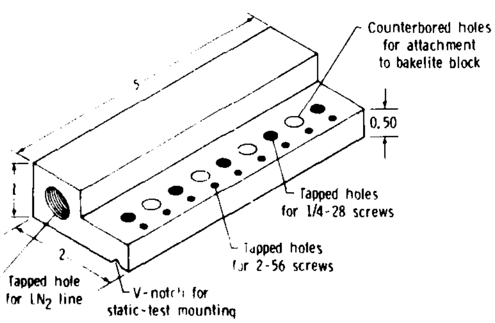


Fig. 4 Assembled test pieces.



(a) Specimen base

Fig. 3 Test specimen parts. Dimensions in inches.

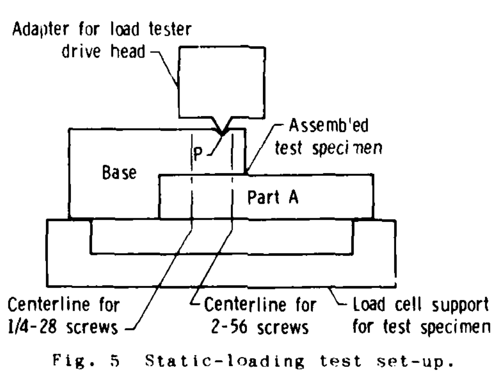


Fig. 5 Static-loading test set-up.

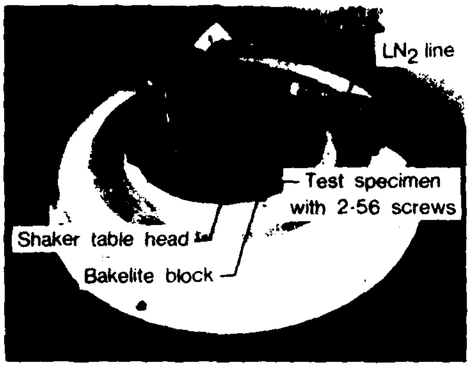


Fig. 6 Test specimen mounted on shaker table.

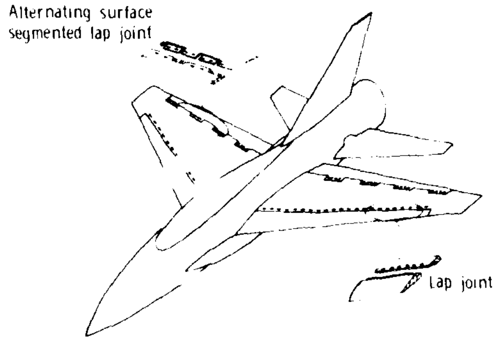


Fig. 9 Pathfinder II model illustrating leading and trailing edge flap attachment.

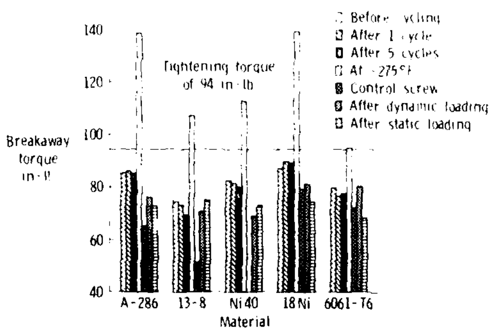


Fig. 7 Breakaway torque value for self-locking Heli-coils used with 1/4-28 screws.

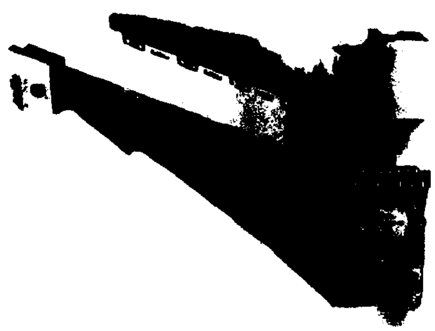


Fig. 10 Proof-of-concept test specimen.

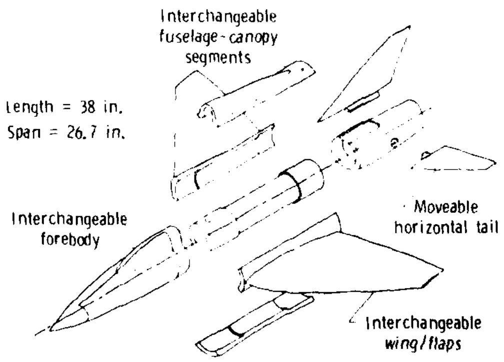


Fig. 8 Pathfinder II.

Fig. 11 Proof-of-concept specimen illustrating detail of alternating surface segmented lap joint.

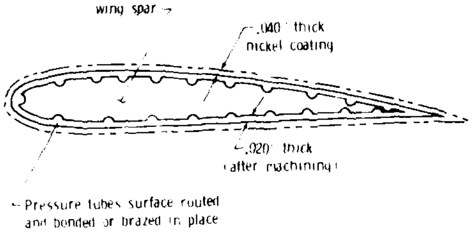


Fig. 12 Nickel plating concept for instrumented wing.

Fig. 15 Wing specimen in cryo static load fixture.

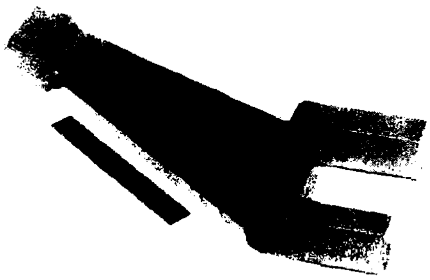


Fig. 13 Wing spar specimen.

Fig. 16 Pathfinder I developmental models.

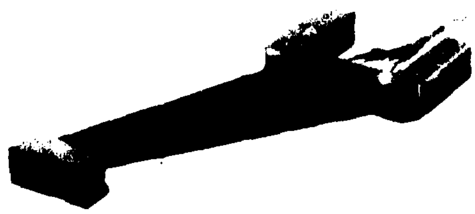


Fig. 14 Wing specimen with tubes installed and fiberglass overwrap.

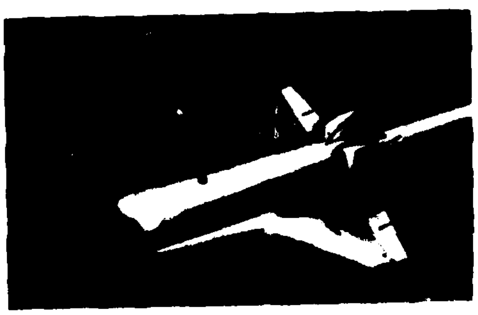


Fig. 17 Shuttle orbiter .02 scale model.

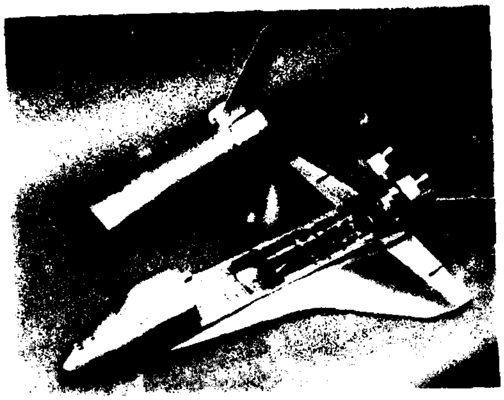


Fig. 18 Shuttle model illustrating remote actuators installation.

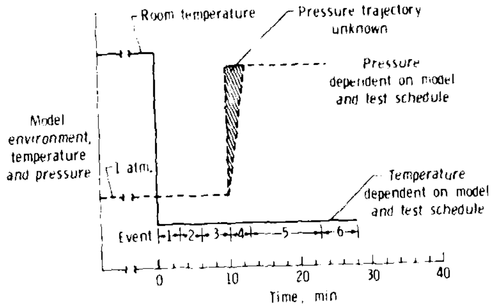


Fig. 21 Post-model maintenance environmental conditions in the NTF.

Fig. 19 Bodies of revolution.

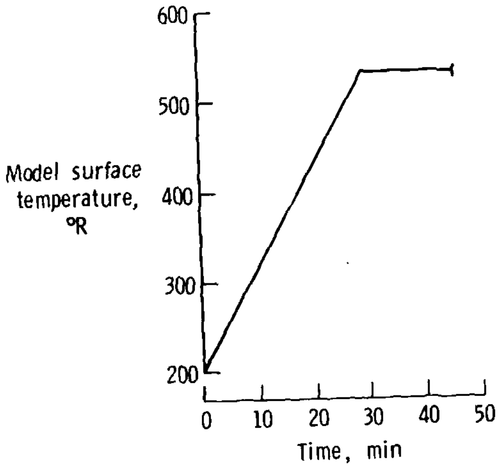


Fig. 22 Warm-up for model maintenance.

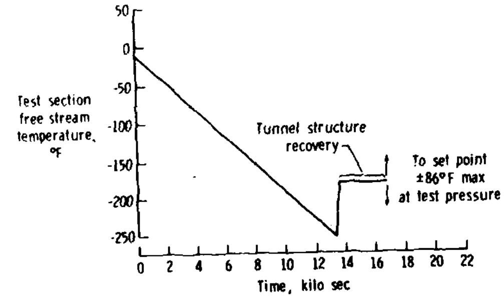


Fig. 20 NTF model system cooldown - test section conditions.

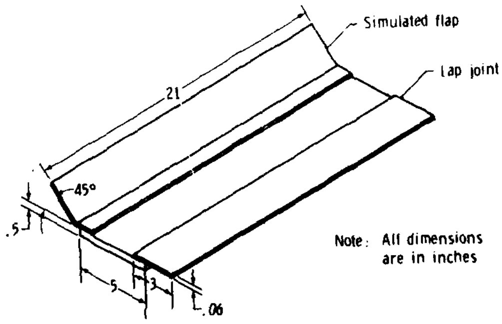


Fig. 23 Thermal loads proof-of-concept test specimens.

CRYOGENIC WIND TUNNEL INSTRUMENTATION

by M. Bazin[1]

With the assistance of Messrs F. Maurer, W. Lorenzmeyer,
K. Brennan and M. Wood of the ETW Working Group 1.

ABSTRACT

When cryogenic wind tunnels are used for simulating high Reynolds numbers close to those encountered in flight, both the model and the wind tunnel instrumentation need to be adapted.

These instrumentation problems are under study both in the United States and in the four European countries involved in the ETW project. A working group, the "WG.1", attached to the technical group responsible for the project, plays a leading and coordinating role in this field and, more generally, in developing the cryogenic technology needed for low temperature tests. This paper is devoted only to the European activities.

The full weighing of the models is still an important part of testing, and places ever-increasing demands on the force level and on the accuracy of the measurements. Complementary and parallel programs have been going on in all four countries to find the best balances possible. Two probative cold balances (one from the NLR and the other from *ONERA*) have been proposed for final approval at the NASA TCT and *ONERA* T2 cryo tunnels.

These balance studies have confirmed the feasibility of a cold instrument. Several technological alternatives (welded or unwelded structure) and several ways of compensating for the thermal effects (direct compensation, computed correction, thermal calibration) seem possible. A special core design is needed to avoid the thermomechanical stresses.

Existing pneumatic and electronic pressure scanners can be used as long as they are enclosed in a heated housing. The housing, though, must be made as small as possible.

Other tests in cryogenic chambers have shown that certain miniaturized unstationary pressure transducers can be used without change.

Accelerometers can also be used in these conditions, *e.g.* for monitoring purposes. But inclinometers will probably have to be enclosed in a warm housing as the model angle of attack is to be measured accurately. Optical devices can be used to measure the inclinometer offset.

Optical procedures are being developed for in-tunnel model deformation measurements. These are simple processes yielding a global rotational value (such as the torsiometer), but there are also more analytical processes using stereo cameras.

Special probes and supports are used, *e.g.* in the T2, to measure the pressure and temperature of the flow without applying thermal or mechanical stresses to the transducer itself. Skin transducers have also been developed.

Finally, model instrumentation calls for developing new machining techniques for pressure holes as small as 0.1 mm. The gearmotors and jacks used in moving the model and parts have also been adapted and tested for use at low temperature.

The results are already encouraging, but work remains to be done in many fields. European organizations have appropriate test facilities for this, with the many cryogenic chambers and the PETW, T2 and KKK wind tunnels.

1 - INTRODUCTION

Using cryogenics to attain high Reynolds numbers similar to those encountered in flight, in the future European wind tunnel (ETW) and in smaller national facilities, raises questions in the field of measurements and, more generally, as concerns the feasibility of the tests.

This is why the ETW Steering Committee created working group WG.1, with one representative from each of the four countries concerned, and one ETW technical group chairman.

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The group's main objectives are to (Fig. 1):

- *identity* *ETW* testing problems relating to the models and supports, instrumentation and, generally, test techniques and systems
- *recommend* certain actions to the technical group
- encourage and coordinate research in these fields in each country concerned, considering the specific national needs
- exchange data and delegate as best possible the actions of each country in a complementary fashion.

TERMS OF REFERENCE FOR ETW WG1

To identify the technical problems areas relevant to testing in ETW including instrumentation, testing techniques, model design and manufacture

To act in an advisory role and to recommend to TG ETW any necessary actions

To act as a channel of communications and to stimulate and coordinate work on these problems in the participating nations taking into account the national programs.

To encourage actions in the four countries involving national establishments industry and universities

PRESENT WG1 MEMBERS

F MAURER	ETW TG	Chairman
M BAZIN	ONERA	France
K BREMAN	NLR	Netherland
W LORENZ MEYER	DFVLR	Germany
M WOOD	RAE	Great Britain

Fig. 1 - ETW WG.1 Objectives.

The wind tunnel technical group, helped by the recommendations and research of the WG.1, is responsible for conducting a "cryogenic technology" program throughout the wind tunnel definition and construction stages.

Taking a look at the mainstream of research that has been going on in the four countries up till now, a certain overlapping can be observed and, surely, some areas have been left untouched.

It is nonetheless astonishing to observe that the development of adapted multicomponent balances has been the subject of intense activity. The high level of the stresses, (due to the wind tunnel pressurization and the present or foreseeable evolution in aircraft performance) and the accuracy needed (in particular for the drag measurement) already calls for very sophisticated, ever-improving instruments even in today's noncryogenic wind tunnels.

A good way must thus be found to compensate for thermal and thermomechnical stresses through a much larger range of temperatures. As we will see, the warm-housed balance (Fig. 2) was discarded, contrary to the other transducers, because of the special role this transducer plays as one of the elements in the support line, and because of the space taken up inside the model, which is often a *determining factor*.

BALANCE

TYPES OF SOLUTION

	TYPE OF BALANCE	TEMPERATURE	GRADIENT	CALIBRATION	PROBLEM
1	FULLY INSULATED CLAMPS THERMAL INSULATION REGULATED CASING	FIXED (ROOM OR INTERMEDIATE)	NO	SIMPLE	SIZE STING LINE STRENGTH UNIFORM AND CONSTANT TEMPERATURE TO OUTSIDE Δ θ
2	NON INSULATED	ACCORDING TO TUNNEL AND MODEL STING	LIKELY	DIFFERENT θ LEVELS GRADIENTS	TEMPERATURE MEASUREMENTS GRADIENT CORRECTION THERMAL COMPENSATIONS COMPUTATION
3	INTERMEDIATE SOLUTION LOCAL HEATINGS FOR INTERNAL GRADIENT REDUCTION	CONSTANT INSIDE BALANCE	NO	DIFFERENT θ LEVELS	HEATERS MONITORING EFFECTIVENESS

THERMAL ENVIRONMENT

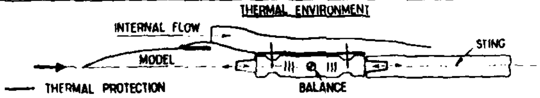

Fig. 2 - Possible balance in cryogenics.

Less time has been devoted to pressure measurements, because of the confidence in commercially available products. This is justified by the experience acquired in current installations, and by additional experiments. The equipment can generally be insulated and reheated, except for the unsteady skin pressure transducers where the sensitive element must be nearly in contact with the cryogenic flow.

The accelerometers or other inclinometers used for getting an accurate measurement of the model angle of attack must also be enclosed in a warm housing. Although the volume of these housings creates another dimensional problem that must be solved for the model cavities, the feasibility of cryogenic testing does not seem to depend crucially on this type of measurement, even though the desired precision is high (0.01°).

Attitude measurements by external optical systems may be an outgrowth of the studies conducted to define a means of characterizing model deformation.

This is a relatively recent need, though global deformation measurements have been made in the past in the large wind tunnels, often by photography.

The desired improvement in measurement accuracy, the increased importance of deformation in pressurized wind tunnels at high Reynolds numbers, the improvement of computer systems working in parallel with the wind tunnel measurements, all lead to a much greater concern for the identification of the real forms of the model during the test. Such measurement systems will of course have to be adapted to cryogenics.

Finally, the model pressure tubing and moving element motor systems are commonly included in the "instrumentation" group of problems. The thinness of the boundary layer at high Reynolds numbers creates new construction problems as concerns the model surfacing and orifice dimensions. Similarly, the cold operation of the motor systems and displacement transducers will require adapted technology, first qualified by low temperature tests.

The European cryogenics program has not as of yet confronted many of the problems already listed, *e.g.* the visualization problems of the transition, skin flow or total flow (vortices), for which test facilities such as *ONERA*'s T2, the KKK of the *DFVLR* or even the PETW must be used.

There is also the question of transferring special tests such as motorized tests with pressurized jets and turbine power simulators (TPS) to the cryogenic domain, along with weighing of model elements (control surfaces, nacelle, rear part), air intake and afterbody tests as well as flutter tests, for which cryogenics offers possibilities of better similitude. It is easy to imagine the work that remains to be done to adapt to cryogenics the special instrumentation used in these tests. The WG.1 has now drawn up a list of these priorities. The most urgent need is related to the impact that a given requirement, whether a priority item or not, may have on the ETW design.

This paper presents a few significant examples of acquired results that give reason for us to look forward to the most classical tests—overall weighings and pressure measurements—in the ETW with confidence. Although the research from the four countries is mentioned in this paper, thanks to the collaboration of the other WG.1 members, for the sake of convenience the author has preferred to present those contributions he knows best, to illustrate the state of the instrumentation we can expect to see used in the ETW. This presentation is all the less representative of the full volume of research in the four ETW countries as the WG.1 has touched upon many subjects other than instrumentation (cryogenic materials, supports, models, etc.).

2 - Multicomponent Sting Balances

2.1 - *General Survey of Activities in Europe*

Figure 2 lists the various types of internal balance that could be used for cryogenic wind tunnel testing:

- a completely insulated balance in a temperature-regulated casing
- an uninsulated "cold" balance
- a balance with local reheating elements to limit the thermal gradients.

Aside from some research done by MBB in 1979 [1] on a conventional 1.5-inch Able balance with a heated casing, for which some data is shown in figure 3, all of the research programs have been oriented toward uninsulated balances.

Essentially, insulated balances were dropped because they were too bulky and presented mechanical strength difficulties.

While the NLR was designing and constructing a probative balance [2], the RAE was constructing a "test bench", a veritable miniature cryogenic wind tunnel (25 m/s, 0.3 m × 0.3 m) to qualify the balance before testing the model in the TCT in collaboration with NASA.

At the same time, *ONERA* launched a preliminary study program with mechanical test pieces, with the purpose of defining the best metal and gages to be used and developing thermal compensation methods that could be extended to the domain concerned. The final goal was to define the qualified probative balance used in the T2 tunnel [4 and 5].

After the first few dynamometer tests, the *DFVLR* designed and constructed a six-component balance whose behavior was identified in a cryogenic chamber [6]. MBB/VFW designed and qualified a welded balance in a cryogenic chamber [7].

On request from the RAE, the *Elven Precision* company designed a new central core structure [8], which has yet to be qualified experimentally. In this structure, the axial rigidity is concentrated (for 90%)

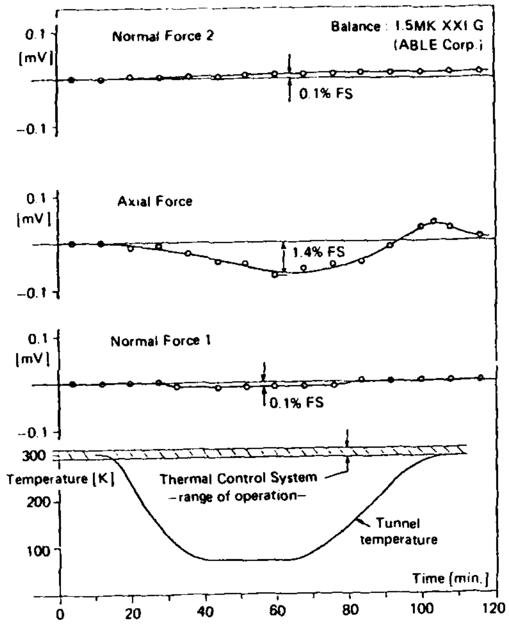

Fig. 3 - Behavior of the Able MK XXI balance with heated casing (MBB data).

at a single point close to the drag dynamometers, located at one end of the balance (Figs. 4 and 5). This provides a better longitudinal and lateral symmetry and, theoretically, allows better thermal circulation because of the central core.

As problems related to the heat transfers between the model and the balance are of a determining nature, a theoretical research program has been launched on this subject.

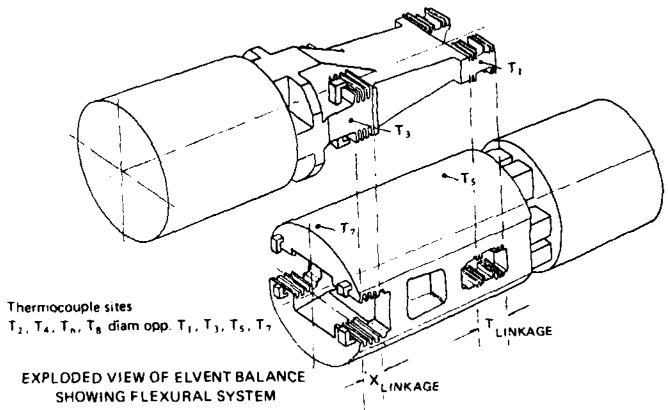

Fig. 4 - Exploded view of the assymetrical structure made by Elven Precision.

Fig. 5 - Elven Precision *balance (photo).*

Two heat transfer calculations were made in an effort to protect the thermal gradient in the model and balance: the first, by Oxford University [9 and 10], is for a delta wing model with a cold balance; the second, by the University of Essen, is more recent and considers a finelly modeled (nearly 2,000 nodes) fighter aircraft with its balance going through the temperature changes, with various hypotheses of convection (forced or not) during the balance cooling and reheating sequences.

2.2 - *NLR 771 Balance* [2] (Fig. 6)

Development studies were started in 1979 to find an insulated balance that can be used in cryogenics. The "cold" alternative was chosen because uninsulated dynamometric elements were needed anyway, for local weighings, but also to avoid difficult dimensional problems for the main balance, in particular for the permeable fighter aircraft fuselages.

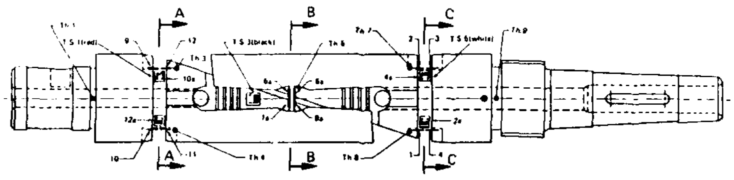

Fig. 6 - NLR 771 Balance.

The basic principle was to use a conventional design but with specially chosen materials. Temperature measurements were then taken at numerous points on the balance, to compute the temperature corrections needed. These were assumed to be reproducible even in the case of transients.

The design operation conditions with combined loads and a safety factor of 5.5, are:

X (drag)	111 N
Y (side force)	300 N
Z (lift)	890 N
L (roll)	14.5 Nm
M (pitch)	28 Nm
N (yaw)	13 Nm.

The balance measures *X*, *Z* and *M*.

The balance is a monoblock structure. Its dimensions (dia. 1", *l* = 225 mm) and fittings were designed for tests in the NASA TCT tunnel (0.3 m). No thermal insulation was provided for at the attachments.

A maraging 250 steel (Vakumelt Ultrafort 301 at 175 hbar) was chosen in agreement with NASA, but the NLR says that a maraging 200 would have been good choice too.

The structure is fitted with *Micro Measurements* SK 11 031 CF 350 gages protected by M-Bond 43 B.

There are three measurement bridges which, in the final configuration (after modifications subsequent to the initial testing in a cryogenic chamber), includes four additional transverse gages that reduce the hysteresis effects for the bending bridges (R1 and R3) and two Wheatstone bridges connected in parallel on either side of the balance, for the drag (bridge R2). In all, then, there are 24 gages + ten thermocouples and six temperature transducers (Fig. 7). The tests show that the bending bridges behave satisfactorily, with a unique zero drift relation as a function of the temperature, regardless of the cooling rate. On the other hand, an added thermomechanical stress appears in the drag bridge when the thermal gradient is high (1° for curve I and 20° for curve II), because of the high 10 K/mn cooling rate (Fig. 8).
It is possible to separate these stresses and to determine a gradient correction law (Fig. 9). These zero corrections are second- and third-order polynomials.

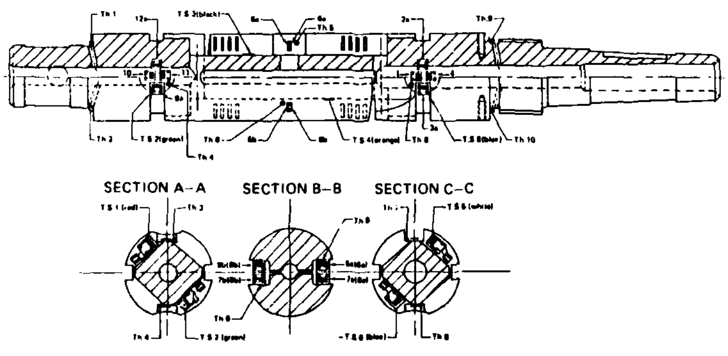

Fig. 7 - Instrumentation of the 771 balance.

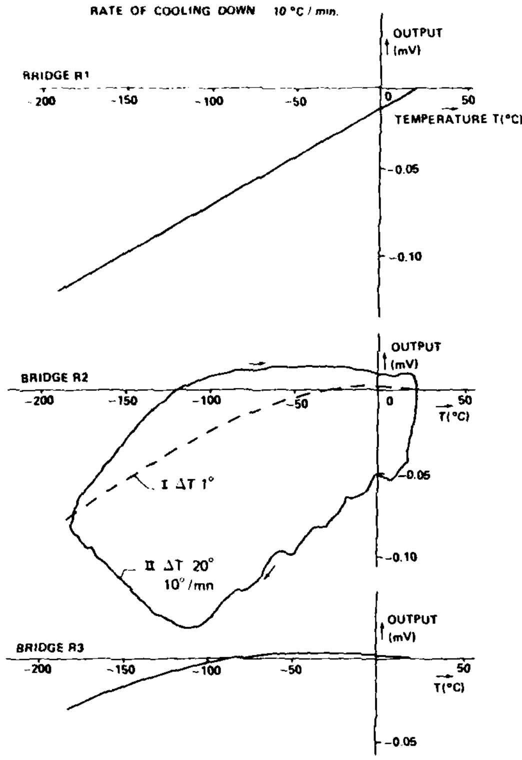

Fig. 8 - NLR 771 balance zero drift.

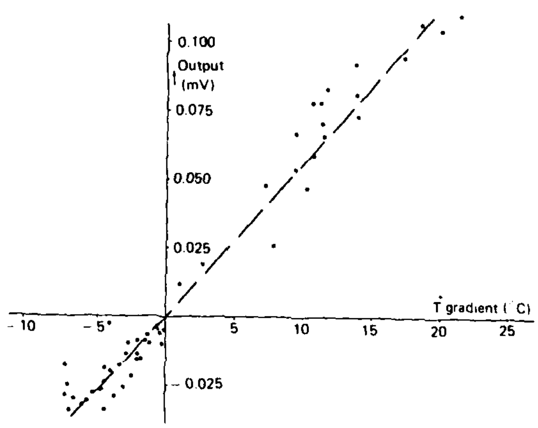

Fig. 9 - NLR 771 balance Effect of the thermal gradient on bridge R2.

The sensitivity variation is small (1.3% for the bending bridges and 2.7% for the drag bridge), and is reproducible and linear from 300 K to 90 K. NASA's observations on the reduced change of thermal sensitivity of the bridges including the tranverse gages, are thus confirmed.

The accuracy of the balance, once modified after the cryogenic chamber tests, is shown in figure 10, giving of the quadratic mean deviation and the maximum deviation. The drag accuracy is not satisfactory because of the thermomechanical stresses induced by the thermal gradients in the center part. An effort is thus needed to solve this problem, and the central core will probably have to be redesigned.

To determine the gradient effects under conditions that are more like wind tunnel test conditions, the balance was tested in the RAE test bench (Fig. 11), with and without the protective sheath that modifies the convection and radiation conditions as would a fuselage [11 and 12]. In addition to confirming the operation of the balance under more realistic conditions than the cryogenic chamber, it was observed that the temperature distributions were greatly affected by the sheath (Fig. 12). This confirms the importance of the temperature variation conditions demonstrated by the Oxford University calculation. The difference in figure 12 can be explained by a preponderance of heat transfer at the ends of the balance in the first case while, with the sheath, the temperature is established by conduction through the balance itself.

	ΔR_1 (%) Bending	ΔR_2 (%) Drag	ΔR_3 (%) Bending
ACCURACY OF THE BALANCE AT ROOM TEMPERATURE	.06(.16)	.13(.28)	.11(.32)
ACCURACY OF CORRECTIONS ON ZERO SHIFT CAUSED BY APPARENT STRAIN AND SENSITIVITY SHIFT ON LATENT OUTPUT	.05(.08)	.21(.43)	.08(.14)
ACCURACY OF CORRECTION ON ZERO SHIFT CAUSED BY TEMPERATURE GRADIENTS	–	.46(1.31)	–
ACCURACY OF CORRECTION ON SENSITIVITY	.08(.14)	.06(.14)	.07(.13)
[illegible]AL MEAN DEVIATION	.19	.56	.26

Fig. 10 - Estimate of the NLR 771 balance accuracy between 90 and 300 K.

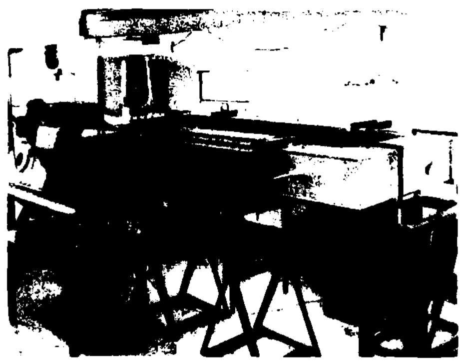

Fig. 11 - Cryogenic circuit at the RAE Bedford installation.

The effect of the sheath on the thermomechanical stresses speaks for itself (Figs. 12 and 13): with the sheath, the X error (Fig. 13) goes from 8% to 2%, while the uniformization time increases (the thermal mass of the model was represented by a block fixed upstream of the balance).

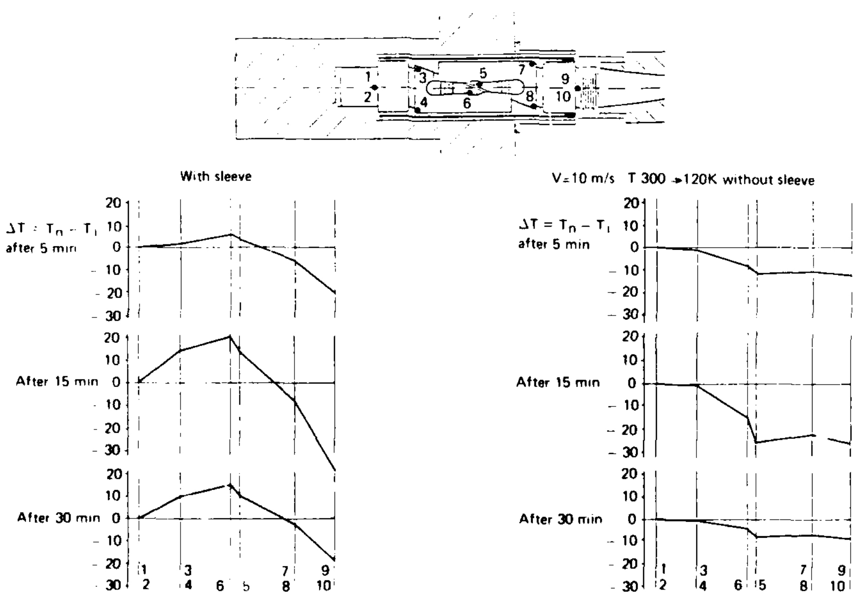

Fig. 12 - NLR balance test at the RAE.

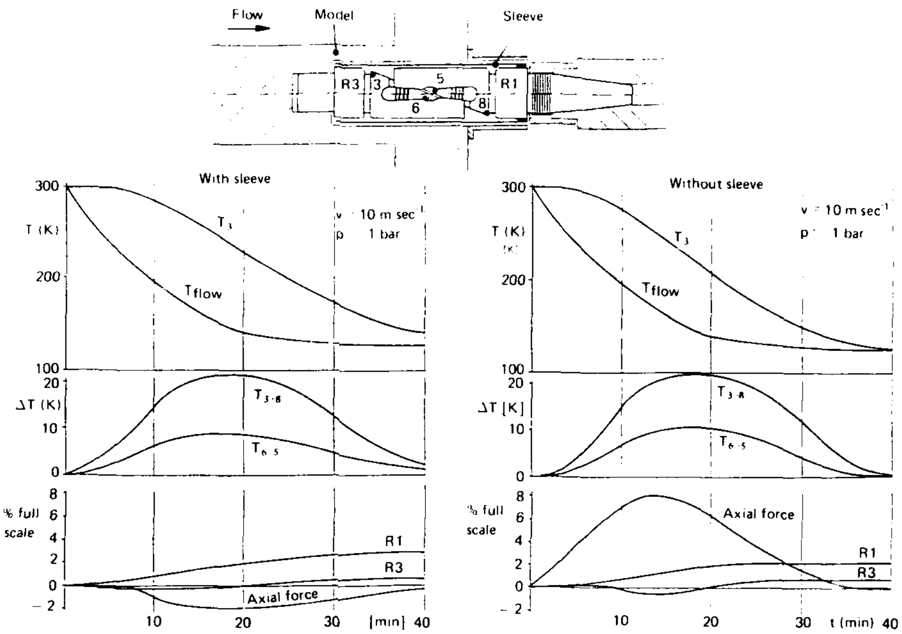

Fig. 13 - RAE test of the NLR balance.

These tests thus showed how important it was to analyze closely the internal temperatures and the exact conditions in which the balance undergoes the temperature level changes. They also confirm the advantage of the finite element calculations, for which the starting hypothesis must be verified by realistic experiments.

Finally, the balance was tested in the TCT. The tests generated the temperature distribution in the balance and the stabilization time for the model-balance and sting assembly, and also established the dynamometric behavior of the balance in a domain comparable to the one in NASA's HRC2 balance test.

The data analysis should be available in the first quarter of 1985.

The balance temperature variations were 50 K for 30 to 60 sec, and the general cooling from 300 to 100 K was carried out at a rate of 10 K/s. The gradient in the balance did not go above 12 K, and was distributed symetrically. It would seem that the gradients were high in these TCT tests, with the protective sheath, which confirms the importance of the convection in the space around the balance.

2.3 - *ONERA 24 mm dia. cryogenic balance* [5 and 13].

ONERA's progress was more gradual because of the time devoted to the preliminary study of the materials, of the strain gage components and of the gage behavior on the various possible base structure materials, and also the time needed for several experiments in a cryogenic environment, using dynamometer test pieces, which were also used to improve the conventional thermal compensation method in the bridges.

The ten dynamometric test pieces used in the tests were triangular and of identical dimensions, which made handling and experimentation easier. The usable service area is large enough for the three bridges comprising four gages each, and for various resistors (Fig. 14).

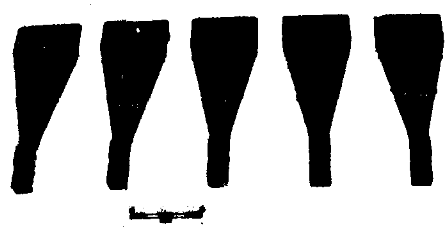

Fig. 14 - ONERA dynamometric test pieces.

AD-A161 833 SPECIAL COURSE ON CRYOGENIC TECHNOLOGY FOR WIND TUNNEL TESTING(U) ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT NEUILLY-SUR-SEINE (FRANCE) 2/5

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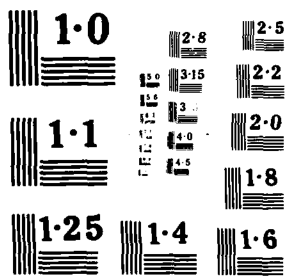
1·0
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Various types of steel were studied, including the V 300 (45 SCD6) spring steel usually used for conventional *ONERA* balances. Armco 15-5-PH stainless steel, similar to 17-4-PH used by most dynamometer manufacturers, was also used along with various types of maraging steel recommended for cryogenics because their resilience decreases little with the cold. Two other alloys, the Fe-Ni alloy Durinval C and beryllium bronze, were also chosen because of their special thermal characteristics, in addition to their elastic qualities.

The test pieces included either two or three bridges, consisting of gages made of different alloys. These alloys were: Karma (nickel-chrome), recommended for cryogenics (three types were tested), grade A-06 constantan used at atmospheric temperature for precision dynamometers, and platinum-tungsten. The latter material has a higher *k* factor than the alloys (4.5 instead of 2), which varies with the temperature in the same proportion as the Young's modulus of the V 300 steel. This means that dynamometers made of this material self-compensate for the temperature coefficient sensitivity. Four types of adhesive were also tested.

Each test piece, mounted on a frame with the holes in its base, was bent under a normal force applied to a point engraved at the apex of the test piece triangle. The relative stresses and strains on the center part of the test piece, of constant 2 mm thickness, is uniform over the entire surface, which makes it easier to compare the bridges. The forces were applied with weights, in increasing and decreasing increments. The bridges were supplied with a regulated 8 V direct current.

The dynamometric sensitivity, hysteresis and creep characteristics of the test pieces were determined for each bridge, for various relative strains up to a maximum 1mm/m , and for various temperature levels between 100 K and 300 K.

The hysteresis and creep effects largely characterize the measuring accuracy. These stresses are due to the test piece metal and to the gages and adhesives used. The data show that their relative importance, which is 1×10^{-3} at atmospheric temperature, decreases as the temperature goes down.

The temperature varies the resistance of the gages and, consequently, the zero (no-load signal) of the bridges, if the thermal variation of the four arms of the bridges (gages + wires) are not equal. It also varies the dynamometric sensitivity (signal/load ratio) of the bridges. These two types of variation differ depending on the gages and on the metal they are bonded to. In effect, they depend on the expansion coefficients and on the thermal coefficients *CTR*, *CTK* and *CTE* specific to the gages and to the materials. It is thus possible to minimize these defects by a proper choice of the constituent materials [4].

The resistance, zero and sensitivity of all of the bridges were measured between 100 and 300 K. It was shown that, for the steel test pieces, the variations were the smallest with the Karma gages; but these gages are most often nonlinear in the thermal domain considered. Special processes have been developed to linearize and compensate the zero and sensitivity variations with a good degree of precision, regardless of the sense of curvature, in the bridges themselves.

The tests on the test pieces also made it possible to study the effect the protective products have on the heat dissipation of the gages, to determine the effects of the cold on the stiffness of the components bonded to the test piece, and to test the strength and reliability of these components under the combined effects of the cold (120 K) and mechanical vibrations (up to 1 million cycles, amplitude ± 1 mm/m, frequency 10 Hz). All of the data acquired during the preliminary experiments, aimed at controlling the zero and sensitivity drifts, led to the decision to construct a cold balance. The study of a balance structure minimizing the thermomechanical effects was launched.

In addition to its gage bridges, the balance (Fig. 15) includes controlled heating devices for creating artificial thermal gradients, to study their effects. The dimensions and openings in the balance were designed so the balance could be calibrated in the cryogenic chamber and then serve later in aerodynamics qualification tests in the *CERT* T2 cryo wind tunnel.

Fig. 15 - ONERA *Cryogenic balance.*

The balance, made of Marval 18 maraging steel treated to obtain a $1{,}700\ N/mm^2$ rupture strength, has an outer diameter of 24 mm and an overall length of 210 mm (Fig. 15). Two cylindrical metal protective casings are fastened to the front and rear.

The instrument was designed to measure the three force components (X, Z, M), but the structure can also measure (Y, N, L). It was designed and optimized, especially for the X measurement part, by a finite element computation program. The nominal capabilities are:

$X = \pm\ 250$ N
$Z = \pm\ 800$ N
$M = \pm\ 65$ N-m.

The axial X component is measured by two gages working as shear gages, placed in tandem at the center of the balance. Their axial rigidity is large compared with that of the vertical blades (calculated ratio of 12.8) constituting the elastic parallelogram that encloses them and decouples them from the other components. The insensitivity of the X measurements to the thermomechanical forces was demonstrated in a prior calculation.

The balance is fitted with five bridges of grade SK 13 Karma gages with a resistance of 350 Ω. The three bridges measuring the (X, Z, M) components include eight specially arranged gages (laid lengthwise and crosswise like the bridge arms) to minimize the temperature effect. Two other bridges, made of four identical gages arranged in a more conventional fashion, are used as references for comparing the thermal stresses and can, if needed, measure the Y and N components. The rest of the instrumentation consists of four film resistors for heating, and eight Cu-Ct thermocouples placed along the length of the structure to study the thermal gradients and stresses.

The dynamometric calibration of the balance, carried out at atmospheric temperature on a special six-component bench, revealed a very good mechanical behavior. The bridge response to the main stresses is linear. The X bridge sensitivity, for example, is 37 µV/N (with a 6 V supply). The interactions are relatively small. The measurement accuracy is 0.5×10^{-3} of full range.

The zero drift of all of the bridges and half-bridges was measured between + 20 and - 180° C. These variations, which were more or less curved and varied more or less from one bridge to the next, were linearized and compensated by the processes developed during the tests on the test pieces. The residual slopes and curvatures are less than 1×10^{-3}.

The bridge temperature sensitivity variations were thus determined by calibrations at different temperature levels. The sensitivity decreases with the cold, but the bridge linearity and hysteresis remains very good throughout the entire temperature domain explored. The relative variations from + 20° C to - 180° C are $- 12.4 \times 10^{-3}$ for the X bridge, $- 19 \times 10^{-3}$ for the specially wired Z and M bridges, and -30.6×10^{-3} for the reference bridges. They are 1.6 times less, and also more linear, for the special bridges than for conventional bridges. Compensation was provided for these variations in the X, Z and M bridges, and figure 16 shows the quality of the zero and sensitivity corrections for the X bridge.

The effect of the thermal gradients was studied, first by rapidly changing the temperature of the chamber containing the balance.

The bridges, including the drag bridge, were practically unaffected by the thermomechanical stresses. In the first tests, where the balance was stripped of its protection, the differential thermocouple effects of the internal wire soldering in three of the ten half-bridges, probably due to the different sizes and thermal inertias, were shown by cutting off or reversing the electrical power supply. The parasitic effects were very much attenuated once the casings were installed and local protection was provided for the wiring.

For the gradient tests, the balance was first stabilized at - 20° C, -80° C and - 170° C, and was then heated locally by one or another of the resistors bonded to the structure. The results confirmed the previous data (Fig. 16).

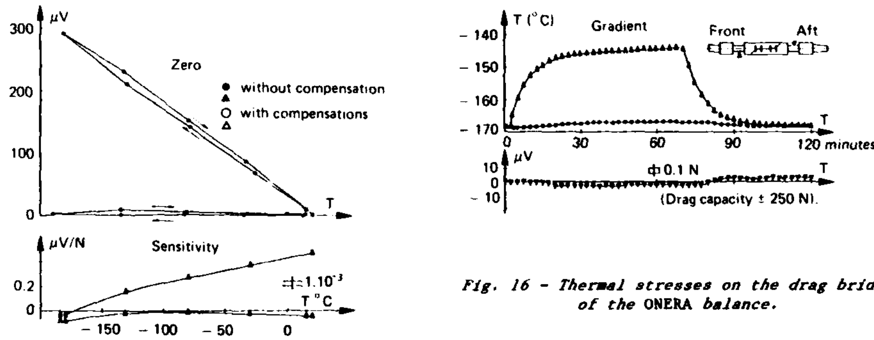


Fig. 16 - Thermal stresses on the drag bridge of the ONERA balance.

Laboratory experiments have thus shown that is possible, just as for the conventional balances, to compensate the thermal effects (zero and sensitivity) and the thermomechanical effects related to gradients up to 20°, in a domair going from 100 to 300 K.

The results obtained on a particular mean-capacity 24 mm dia. balance cannot be generalized without reservation. We know, in particular, that this type of balance becomes more sensitive to the thermomechanical stresses as the dimension and thus the thermal inertias increase.

The final qualification test of the prototype balance thus consisted of an actual test in the T2 wind tunnel. For this test, which was supposed to be as realistic as possible, a simple model had to be created with a support. The assembly had to be dimensioned and designed to fit into the test section. As a blowdown-type wind tunnel was used, the model had to be precooled outside the test section and placed in a steady flow, for measurements to be taken in a stabilized regime. A specific system had to be created for inse ting the model into the test section for these tests. Only the cold blower part of the existing model co ' g system for the wind tunnel (Fig. 17 and 18) in 2D flow could be reused.

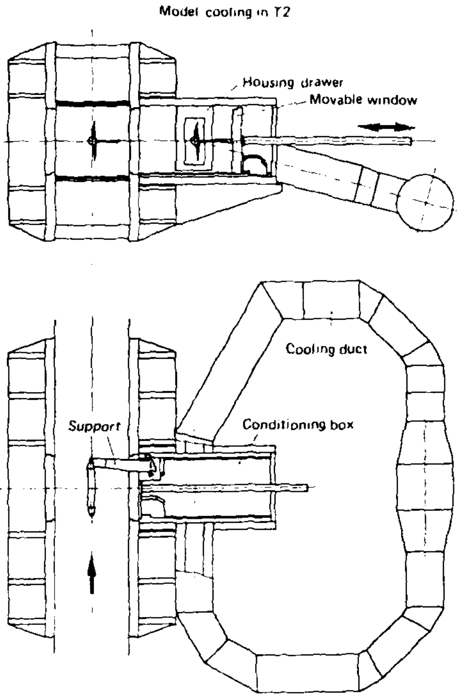
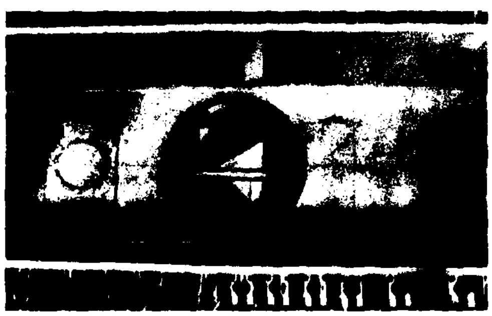


Fig. 17 - Model-balance cooling in the T2 wind tunnel.



Model in cooling chamber

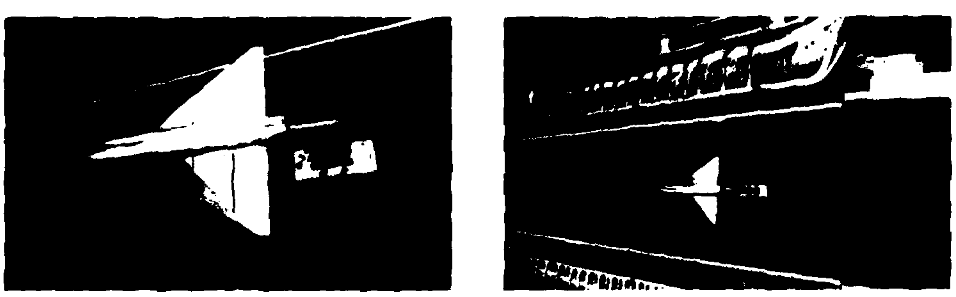


Fig. 18 - ONERA cryogenic balance in the T2.

The purpose of the tests was thus to check the behavior of the balance in the wind tunnel and the accuracy of the instrument under realistic operating conditions. To evaluate this accuracy, the zero returns and any sensitivity drifts had to be analized. It was also interesting to note the temperature variations in the balance.

The model included four thermocouples (three on the wing and one on the fuselage) (Fig. 19). The test program included Mach number variations from 0.6 to 0.8, stagnation pressure variations from 1.5 to 3 bar, stagnation temperature variations from 300 K to 120 K, and model angle of attack step variations.

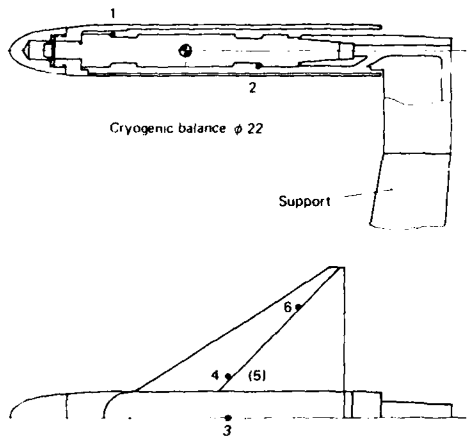
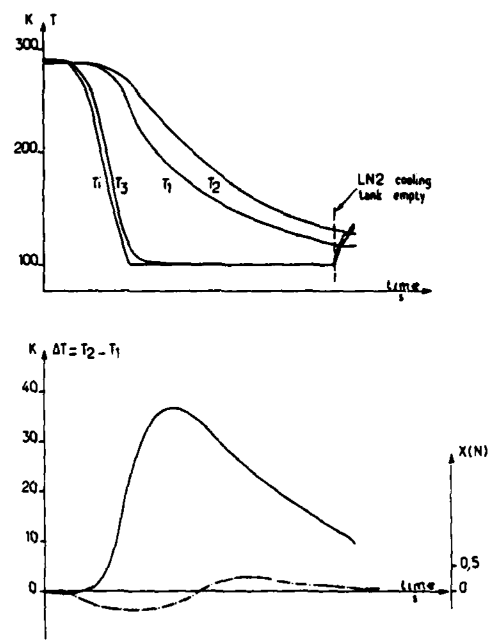


Fig. 19 - Position of the thermocouples on the model and on the balance.

Several difficulties appeared, in particular the formation of ice on the model and sometimes on the balance during precooling. This was due to a faulty seal of the "drawer" from the atmospheric air.

During the 20 K/mn precooling, a thermal gradient reaching 36° was observed in the balance, and the measurement bridge signals vary and gradually return and stabilize. The maximum X error under these conditions is no more than 0.3 N, which confirms the data from calculations and during calibration (Fig. 20).

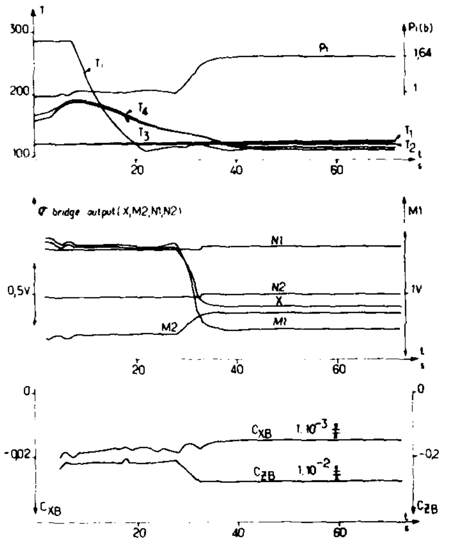


MODEL AND BALANCE COOLING BEFORE RUN 36

Fig. 20 - Balance test in T2.

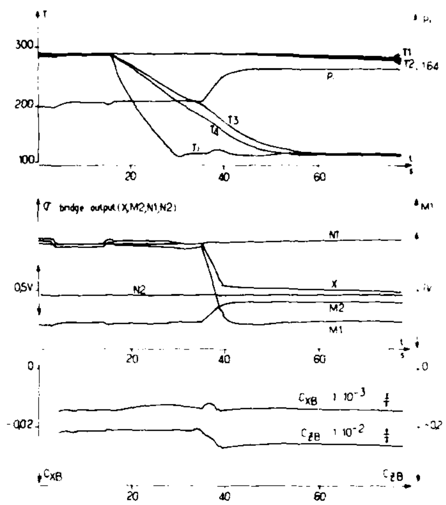
During a blowdown with precooling, which is the way of simulating normal conditions for the balance in a wind tunnel like the ETW, we observe that the balance temperature remains stable as the slight gradient that develops does not exceed some 5°. The result is that the signals are perfectly stable when the flow is stabilized (Fig. 21).

When the model and balance are not cooled beforehand, we observe (Fig. 22) that the model reaches the test section temperature almost uniformly (Δ = 5 K) some ten seconds after the stagnation conditions stabilize, and that the balance drifts slowly (some 10 K) during the blowdown, with a small gradient of 5 K. The drag and lift measurements remain stable. We observe a drift in lateral reference bridge N1 (conventional design) of - 0.26 mN. We may thus conclude that conventional balances can be used in a blowdown tunnel like the T2, with a good temperature compensation at the level of the bridge.



run 36 : M=0.75 Pi=1.64 b Ti=120k with model balance pre-cooling

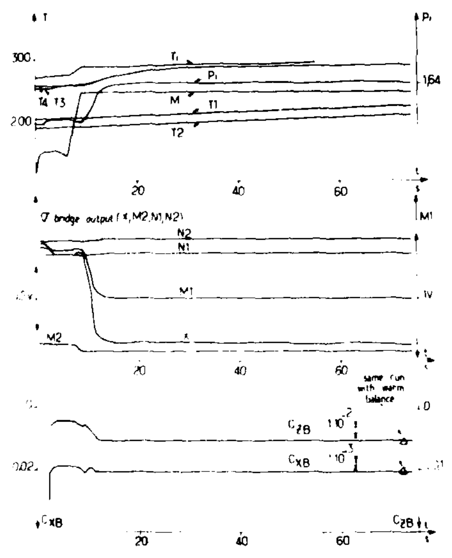
Fig. 21 - Balance test in T2.



run 37 : M=0.754 Pi=1.64b Ti=120k warm balance

Fig. 22 - Balance test in T2.

The last graph presented here (Fig. 23) is for a blowdown at atmopheric temperature, with the model-balance assembly precooled. When the balance remains cold, the model quickly returns to atmospheric temperature. The results obtained from a blowdown at atmospheric temperature with the model and balance uncooled are given in the figure. The comparison demonstrates that the same drag and the same lift are found whether the balance is cold or warm, using the same computation matrix despite the 0.2 K/s thermal drift of the balance and longitudinal gradient 10 K.



run 28 M=0,754 Pi=1,646 Ti=296 with model balance pre-cooling

Fig. 23 - Balance test in T2.

The zero variations of the X bridge, between the time it left the laboratory and the time it returned after 57 blowdowns, corresponds to 2 N, or some 1% of the full range.

2.4 - *DFVLR balance* [6].

After starting with a few dynamometer tests under cryogenic conditions, the *DFVLR* constructed a six-component balance equiped at first with SK09 gages. The structure is made of Vakumelt Ultrafort 301 maraging steel. The diameter is 30 mm (Figs. 24 and 25).

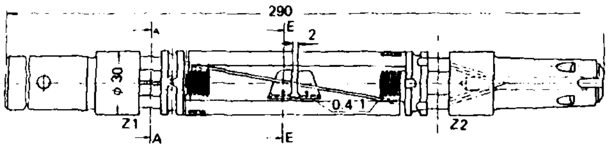
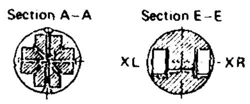


Fig. 24 - DFVLR *six-component balance.*



Load ranges x = 300 N
y = 1000 N
z = 2000 N
L = 5000 Ncm
M = 15000 Ncm
N = 8000 Ncm

Fig. 25 - Components used constructing the DFVLR balance.

Bridge	Z1	Z2	XL	XR
Strain Gauges	SK-09-060PB500	SK-09-060PB500	WK-09-060PB500	WK-09-060PB500
Number of Gauges	8	8	4	4
Bond	M-Bond 610	M-Bond 610	M-Bond 610	M-Bond 610
Solder	361 A-20R	361 A-20R	361 A-20R	361 A-20R *
Solder points	CEG 25C	CEG 25C	CEG 25C	CEG 25C
Coating	M-Bond 43B	M-Bond 43B	M-Bond 43B	M-Bond 43 B
Wiring int.	134 AWQ	Lacquer insulated copper wire (ø 0.1mm)	Lacquer insulated copper wire (ø 0.1mm)	Lacquer insulated copper wire (ø 0.1mm)
ext.	38 MT 746	38 MT 746	38 MT 746	38 MT 746 **
Colour	violet	white	yellow	red

* 63% Sn, 36.65% Pb, 0.35% Sb
** *Thermax Wire;* silverplated, 2.6 Ohm/Meter

The balance was further machined and reinstrumented for thermocouples.

The particular feature of this balance is its heating elements, to make the temperature uniform. These elements are controlled by indications from the thermocouples.

The balance includes four Cu-Ct thermocouples. Two of them are installed between the two conic ends and the dynamometric area. The other two are located in the triangular frame enclosing the drag element.

The front and aft measurement sections include two bridges, Z1 and Z2, with eight gages each. The two drag gages to the left and right of the central part consist of four-gage bridges, denoted X_L for the left and X_R for the right.

The equipment characteristics are: SK.09.060 PB 500 gages for Z1 and Z2, and WK.09.060 PB 500 gages for the other two, adhesive M.610, solder 361 A.20 R.

The bridges are supplied with 5 V dc. The test was carried out in a Cryoson temperature chamber equipped with a system for applying forces and moments to the balance.

A certain number of tests were carried out to determine the bridge zero drifts as the temperature in the chamber was lowered continuously. Going from 194 K to 144 K in 40 min, for example (Fig. 26), bridges Z1 and Z2 gradually vary some - 40 µV. *The drag bridges*, though, vary with sign changes: X_L, the only one shown here, goes down 80 µV in the first minutes and then gradually rises to + 20 µV difference after stabilization at 144 K. This stems from thermomechanical effects.

The zero variations in stabilized steps are approximately + 0.6 µV/K for Z1 and Z2, with slight curvature, while the variations of X_L and X_R, of reverse sign from the preceding ones, show very sharp curvatures.

The relative sensitivity variations with temperature are + 0.07×10^{-3}/K for the Z1 and Z2 bridges, and approximately + 0.2×10^{-3}/K for X_L and X_R (Fig. 27).

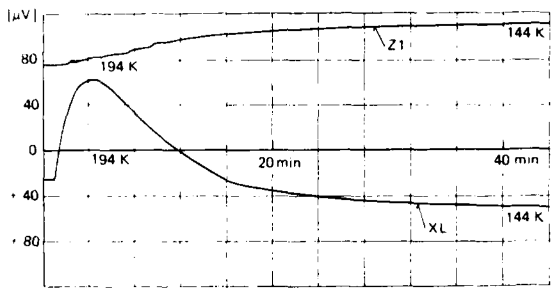


Fig. 26 - Variation of the lift and drag bridges as a function of temperature.

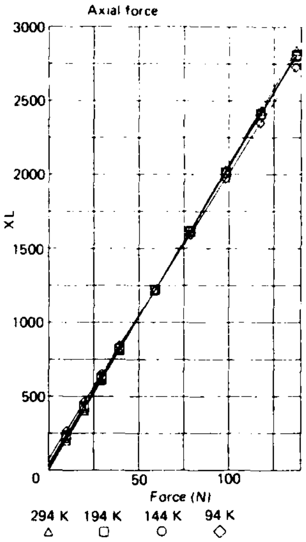


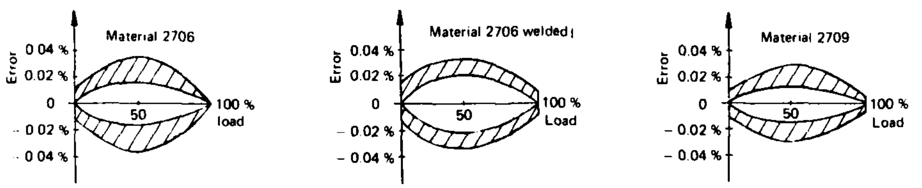
Fig. 27 - Variation of the X_L signals of the DFVLR balance (sensitivity).

2.5 - *MBB/VFW balance* [7].

The particular feature of this cold balance is that it is made from electron-beam welded elements, not electro-erosion machined as the previous ones are (Figs. 28 and 29). Moreover, the thermal effects are corrected for at the analysis stage, with predetermined third-order polynomials. The additional gages are bonded to the elastic parallelogram blades, though, to provide certain thermal corrections for the main drag measurement, by the method M. Dubois developed at *ONERA*.

Fig. 28 - Elements of the MBB/VFW balance before welding.

Fig. 29 - Dynamometric behavior of welded and unwelded steel test pieces (MBB/VFW data).



For the manufacturer, the fact of using the numerical corrections simplifies the balance instrumentation and provides a simple way of correcting for the nonlinearities. This is substantiated by an analysis of the causes for the bridge signal variations and of the orders of magnitude.

Tests were first carried out on three bending bars of the following maraging steels:

- Thyrodur 2706 (X2 NICOMO 1885): 2 bars, nos. 10 and 11
- Thyrodur 2709 (X2 NICOMO 18125): 1 bar, no. 12.

Bar no. 11 was cut in the middle of the dynamometric area and then rewelded by electron beam. The gages were bonded to this welded part, to compare the elastic behavior to that of the other two bars.

The instrumentation was identical on all three bars:

- Gages: *Micro-Measurement* WK.06.125 PC.350
- Adhesive: M.610 (*Micro-Measurements*)
- Internal wiring: 134 AWP, polyurethane insulator AWG 34
- Solder: 361 A.20 R (*Micro-Measurement*).

The three bars were subjected to maximum relative strains of 1.6 mm/m. The bridges were supplied with 5 V dc.

The tests at atmospheric temperature show that the two types of steel behaved similarly. The hysteresis is positive, and that of the welded bar is 1.5 times greater than that of the other two (Fig. 29).

The temperature variation of the zero for the three bridges is in a range $\pm$ 0.5 µV/K ($\pm$ 0.4 $\times 10^{-6}$ [ΔR/R]/K). The relative sensitivity variation with temperature is approximately 0.15 $\cdot 10^{-3}$/K. These variations were not compensated for, but were represented by polynomial expressions.

The results obtained on the three test pieces were used as the basis for defining the six-component "cold" type balance.

The balance is made of Thyrodur 2706 and has a diameter of 50 mm. It is fitted with *Micro Measurement* WK.06 125.BT 350 and MM WK.06 062 AP 350 gages bonded with *Micro Measurement* M. Bond 610. The bridges are supplied in common. Eight temperature measurements are used for the zero and sensitivity corrections, calculated from the laws generated by the test on the test pieces (Figs. 30 and 31).

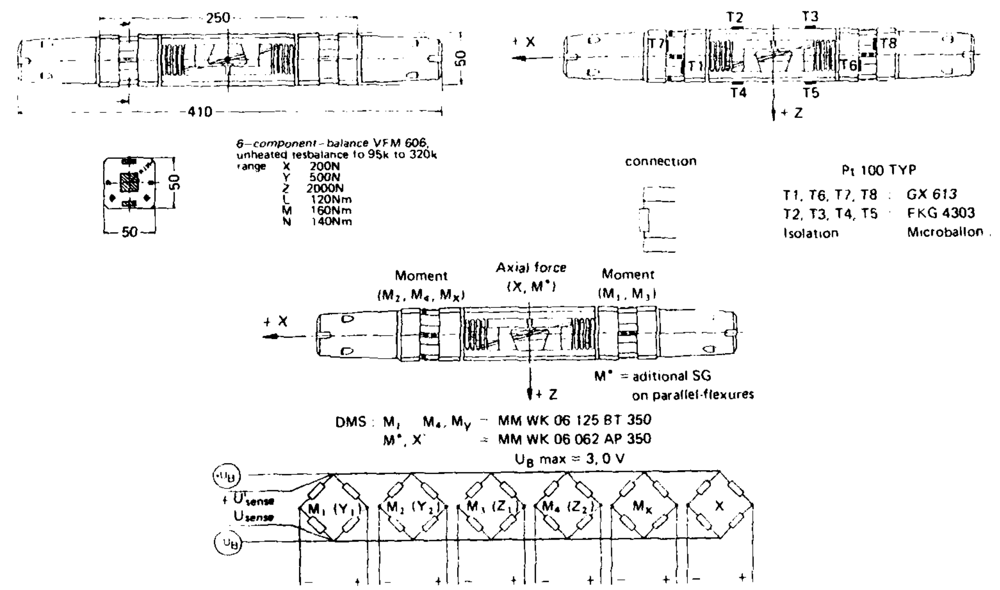


Fig. 30 - MBB/VFW six-component balance.

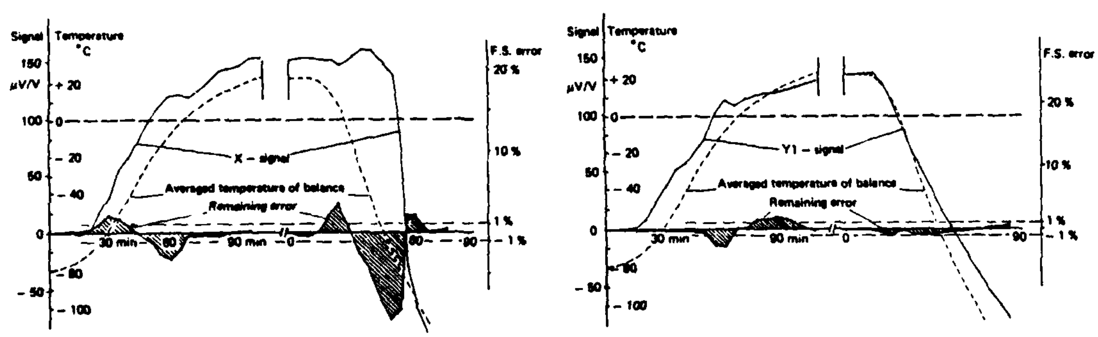


Fig. 31 - Temperature effects on Y1 and X, and errors remaining after corrections

Calibrations at cryogenic temperatures, 200 K and 125 K, show that there were thermal gradient problems making it difficult to measure the temperature with the accuracy required for the correction. Furthermore, the gradients cause thermomechanical stresses in the central part that cannot be properly corrected for.

This experiment, considered as a first attempt, has shown the feasibility of the welded balance. Studies are continuing, to improve the correction for the thermal effects by using the temperature measurement.

2.6 - *Heat transfer calculations*

The heat transfer calculations by finite element method have yielded precious information on the temperature gradients in the balance structure. A preliminary study at Oxford University [9 and 10] with a simplified delta-wing model drew attention to how difficult it is to obtain a model skin temperature with a heated balance that will satisfy the Green, Weeks and Pugh criterion. These calculations with the NLR balance and NASA model show, moreover, the advantage of cooling the model-balance assembly uniformly to 80 K to limit the gradients and the temperature level change times during the tests (Figs. 32 to 34). Recent calculations from the University of Essen also make it possible to determine the behavior of the model and balance (with and without protective sheath) during the temperature conditioning: cooling by liquid nitrogen spray and reheating by radiation or forced convection (Figs. 35 to 38). Experiments are needed to verify these possibilities.

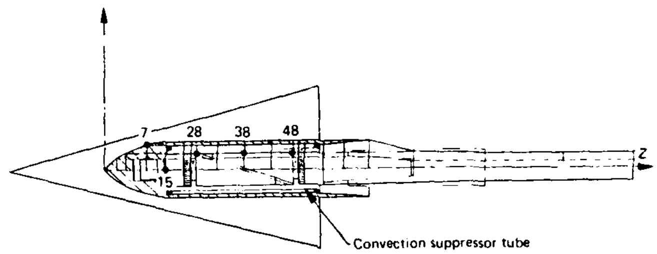


Fig. 32 - Finite element representation of the model at M = 0.85, after cooling to 80 K

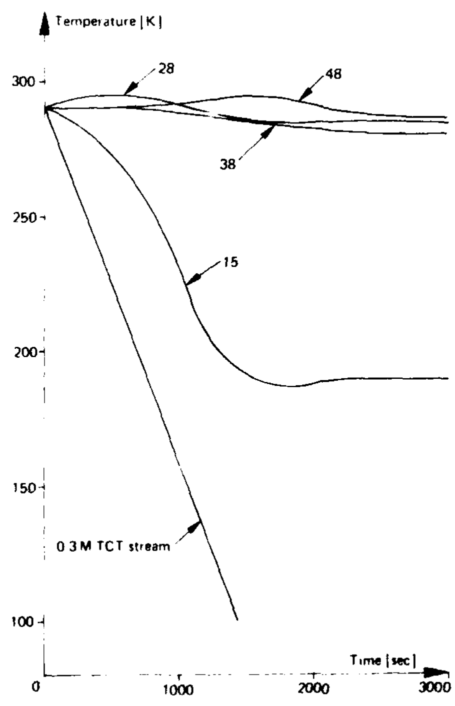


Fig. 33 - Temperature variation at M = 0.85 with reheated balance

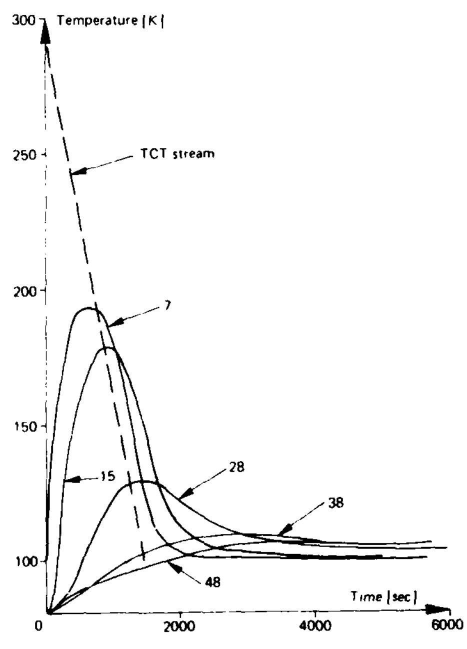


Fig. 34 - Temperature variations for a blowdown at M = 0.85, after cooling to 80 K

No	Procedure	Temperature Change [K]	Heat transfer Values [W·m² K] model surface	flow channel	balance annulus	instru cavity
A	Convection	120 - 300	300	c	c	c[5]
B	Convection	120 - 300	100	c	c	c
C	Convection	120 - 300	5	c	c	c
1	Convection	120 - 300	300	300	5	–
2	Convection	120 - 300	300	300	5	–
3	Convection	120 - 300	5	5	5	–
4	Radiation[1]	120 - 300 (600)	ε 0.07	5	5	–
5	Radiation[2]	120 - 300 (1800)	ε 0.07	5	5	–
6	Spray system[3]	300 - 120 (77)	f (θ)	5	5	–
7	Convection	120 - 300	300	300	c	c
8	Convection[4]	120 - 300	–	5	c	c
9	Convection	120 - 300	300	300	5	–
		300	5	5	5	-
	Spray system	300 - 120 (77)	f (θ)	5	5	–
10	Convection	120 - 300	5	5	5	–
	Spray system	300 - 120 (77)	f (θ)	5	5	–

[1] Lamp heating T_L 600 K
[2] Lamp heating T_L 1600 K
[3] LN_2 - Spray T_s 77 K
[4] H 5 W/m² K at the wing and trail
[5] c conduction

Fig. 35 - Finite element calculation at the University of Essen

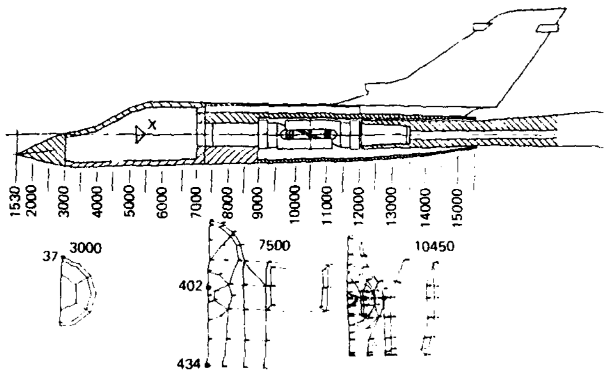


Fig. 36 - Finite element scheme (Essen)

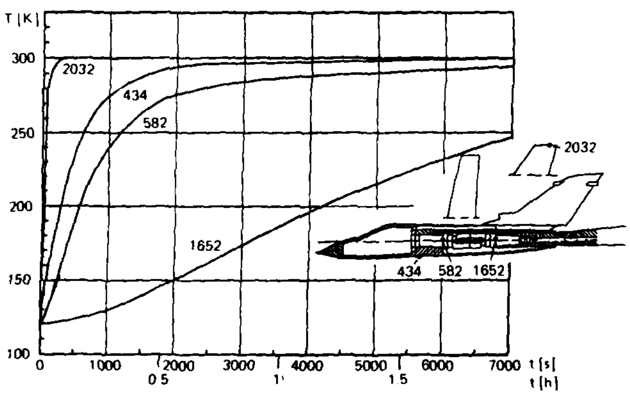


Fig. 37 - Reheating with forced convection and sheath $M = 0.2$, $h = 300\ W/m^2\ K$.

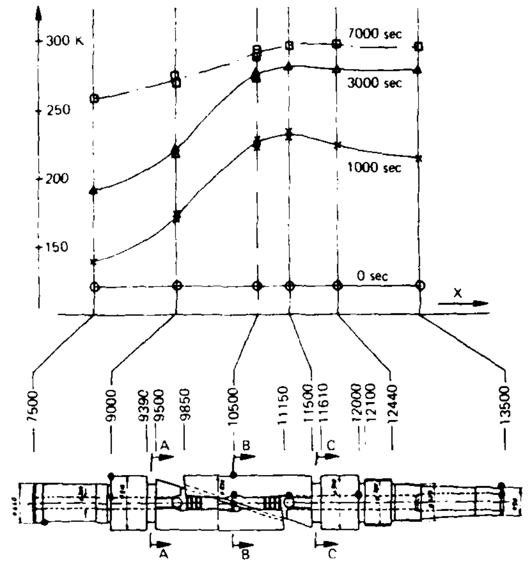


Fig. 38 - Temperature distribution in the balance with the model reheated by natural convection.

2.7 - *Conclusion concerning the balances*

In conclusion, we can say that the various European efforts have validated the concept of the cold balance. The different ways of compensating for the effect of temperature on the bridge zero and sensitivity are very encouraging, whether they involve a direct real compensation or a numerical correction after the measurement.

The problem deserving the most attention is the need to minimize the thermomechanical effects on these structures. *The results obtained with the ONERA* balance show that there should be a solution for this.

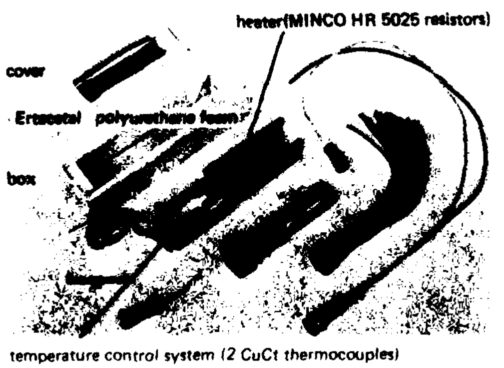
3 - PRESSURE TRANSDUCERS

Three categories of transducers were considered:

a) pneumatic (1 transducer) or electronic (*n* transducers on a single support) scanner system used for measuring many pressure points, generally in a steady flow,
b) autonomous transducers used for a limited number of steady measurements requiring the best possible accuracy,
c) autonomous miniature "unsteady" transducers, often in contact with the flow, or at least in the immediate vincinity of the flow, to minimize the response time.

3.1 - *Scanner system*

For the "Scanivalve" mechanical scanners widely used in wind tunnel applications, it is *impossible* to operate in temperatures very different from atmospheric. A scanner was tested at *ONERA* in an insulated, warmed housing in a cryogenic chamber specially designed for tranducer tests [14] (Fig. 39). The system is well regulated at local temperatures but, as could be expected, it overheats at atmospheric temperatures because of the heat dissipated from the scanner itself. Certain zero and *sensitivity* drifts (up to 4%) result from the thermal differences existing inside the housing. These are detected by eight detector thermocouples.



	Outside housing temperature	
	300 K	120 K
Zero shift/ full range	0	$-4\ 10^{-2}$
Sensitivity/ sensitivity at 300 K	S_0	$0.95\ S_0$
Non linearity/ full range	$1.5\ 10^{-4}$	$1.5\ 10^{-3}$
Hysteresis/ full range	$4\ 10^{-4}$	$4.3\ 10^{-3}$
Repetability (3 measurements)	$3\ 10^{-4}$	$7.8\ 10^{-3}$

Fig. 39 - Scanivalve 48S8, Druck transducer PDCR 22.

The repeatability is $7.8 \cdot 10^{-3}$ of full range (120 K). Frequent calibrations with switched reference pressures should improve the quality of the measurement. The main problem is still the bulk of the warmed housings.

It may be thought that a design of the same type would be usable for electronic scanners (Fig. 40), which are more and more widely used in wind tunnels because they greatly increase the acquisition rate (by as much as 50 times).

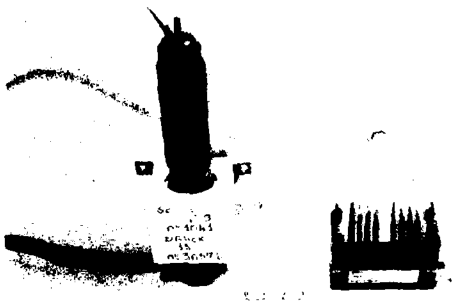


Fig. 40 - Pressure scanners.

These modular pressure scanners dissipate much less heat and make it easier to regulate *the housing* temperature.

Many laboratory tests, followed by wind tunnel tests, evaluating this new *pressure scanner* device have given reason for a certain level of *confidence*. In particular, the system of transducers is no more sensitive to thermal effects around atmospheric temperature than is an autonomous transducer (Fig. 41), and the recalibration possibilities offer the hope of correcting the variations due to the housing regulation and to the thermal inertia of the transducer module. This also entails increasing the volume of the instrument.

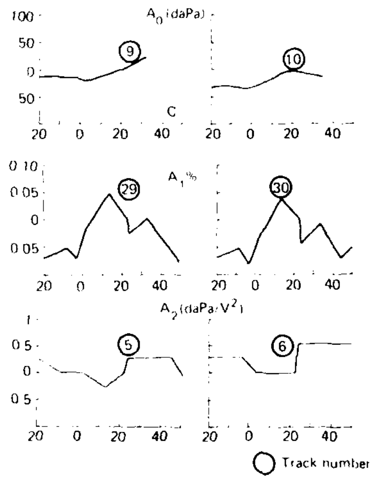


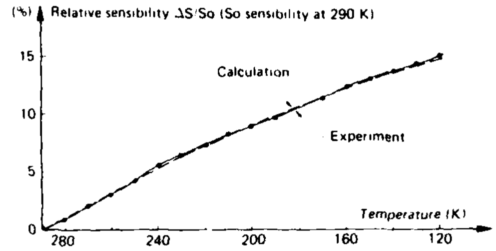
Fig. 41 - Effects of temperature on the transducer coefficients.

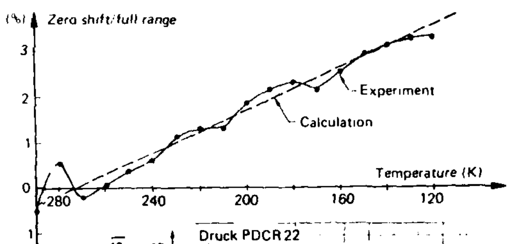
3.2. - *Tranducers alone*

Many tests have been carried out on transducers alone, for example at *MBB* and at *ONERA*, in cryogenic chambers specially designed for this type of calibration. *The ONERA test bench [14] simulates* the temperature, but also the ambient pressure around the transducers, to detect possible thermomechanical or mechanical responses, the pressure to be measured and the reference pressure of the differential transducers. Precautions are taken to avoid convection between the transducers and the reference instrument under atmospheric conditions.

One end of a helical shock tube was cooled to cryogenic level to study how the dynamic characteristics of transducers used for unsteady measurements varied with the cold. To avoid icing, the tube was flushed with dry nitrogen for cooling. A plot is shown in figure 42.

The *MBB* calibration data [15] for various types of resistor or semiconductor transducer (Fig. 43) show wide zero and sensitivity variations that are often nonlinear, and also show hysteresis effects. From this point of view, the resistance transducer behaves better. The *MBB* tests do not confirm *ONERA*'s unsuccessful calibration of a Druck PDCR 22 transducer below 260 K. Further testing is thus needed.





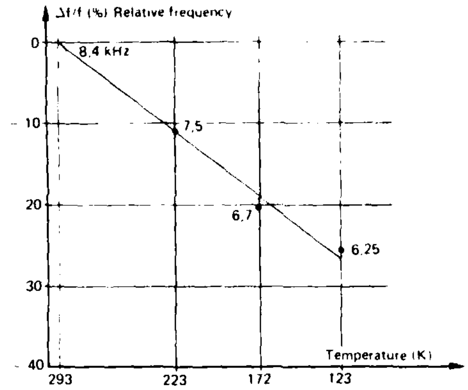
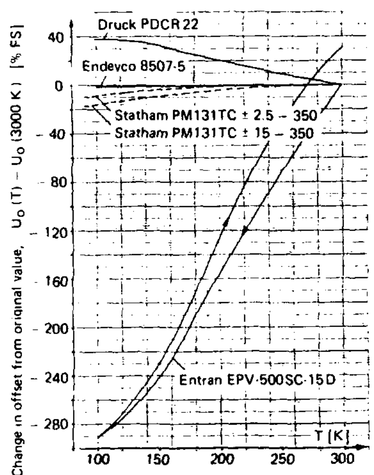


Fig. 42 - Pressure transducer behavior with temperature.



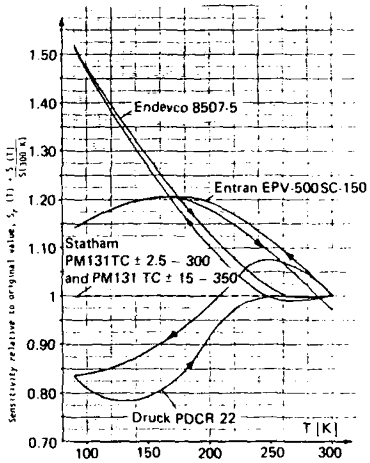


Fig. 43 - Behavior of various pressure transducers with temperature.

The miniature semiconductor transducers are characterized by a weak hysteresis and by the possiblity of functioning correctly at low temperature. However, the wide zero and sensitivity variations cannot be compensated for and temperature corrections thus have to be provided for these transducers, which are generally used without thermal protection.

3.3 - *Use of the pressure transducers*

When the *ONERA CERT* T2 wind tunnel was converted for cryogenics, this provided an opportunity for using some pressure transducers under cryogenic conditions, although these were most often the transducers measuring the flow characteristics, as the model's gages are placed outside the test section and are not in contact with the cold medium.

The T2 team set up a small calibration bench for its own needs, with a cooling rate variation control to detect any gradients. The calibrations were also carried out in the T'2 and T'3 wind tunnels. Among the various transducers tested, the Kulite XCQ 093 transducer (K-type doping, silicon membrane) was adopted for a boundary layer/wake probe. The original compensation was removed, to decrease the non-linearities, and a dual system is used for measuring the voltage and current at the transducer terminals. Two laws, each depending only on the current, express both the zero variations and the sensitivity variations as a function of temperature and eliminate the *T* measurement errors due to the gradients. The bridge resistance is, in effect, a direct function of the temperature.

The transducer is mounted in a PTFE Teflon insulating ring in the probe. The probe body can be fitted with different end pieces adapted to the type of measurement to be taken (Fig. 44).

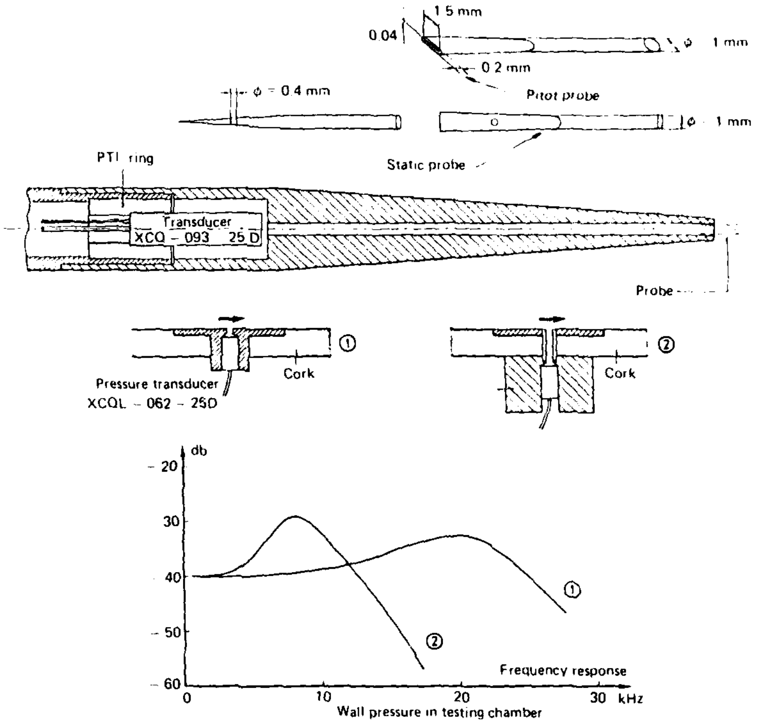


Fig. 44 - Pressure measurements at the T2.

To study the boundary layer noises, the *CERT* tested two wall mounts with different passbands. The second mount is preferred, though, because of the transducer temperature stability during the few minutes of testing. Another wall mount, derived from the probe described above, is used successfully without temperature effects. For a prolonged use, corrections are possible as they are for the probe.

Between 1982 and 1984, 13 *Kulite* and *Endevco* transducers were tested at the CERT, either individually or mounted in a probe. These tests confirm the better behavior of the *Kulite* model above. New, more compact (4 mm diameter instead of 6 mm) measurement probes have been constructed and qualified. The insulating ring has been replaced by a Teflon film providing the seal.

The situation thus seems rather favorable for the pressure measurements, although using a warm housing for the scanners or individual transducer load down the model, by nature. The T2 experience confirms that certain miniature unsteady transducers can be used directly.

4 - *Other Transducers*

4.1 - Accelerometers

MBB has tested an *Endevco* 272 piezo crystal transducer and a smaller *Kulite* GY 125 10 piezo resistance transducer at different temperatures, using an 1151 shaker.

The temperature can change the measurement signal by 2%, with the first accelerometer, whereas it affects the Kulite transducer measurements by 5%. However, this latter transducer is till usable for monitoring, which is of great interest because of its dimensions.

However, for the accelerometers used as inclinometers, this first result is insufficent for the precise angle of attack data needed. For this application, a high quality warmed housing will probably be necessary. *It remains to be verified that this will suffice.*

4.2 - *Temperature measurements*

As man transducers have the defect of acting as a "thermometer", measuring the temperature should, in principle, be one of the simplest problems to solve. The T2 experience confirms that of the simplest cryogenic chambers used here and there: various transducers, and the thermocouple in particular, can be used without problem. The cryogenic conditions do not make it any more difficult to get very precise temperature measurements.

Copper-Constantan *RdF* couples are commonly used at the T2. The solder is encased in a *fiber-resin* plate 15/100 mm thick and 4 mm wide. The connections are remote, at atmospheric temperature. Hardwood supports are used. Temperature fluctuations are a little more tricky to measure, especially at high dynamic pressure.

Stagnation temperature fluctuations at the T2 are measured by a Tungsten "cold wire" 9 µm in diameter, supplied with the constant current $I = 3$ mA. The wire response is correct up to 50 Hz.

The thermal turbulence is measured with probes, consisting of a hardwood plate fitted with copper-constantan RdF thermocouples (recovery factor 0.8) (Fig. 45).

The readings from these various transducers for a real wind tunnel test are compared in figure 46.

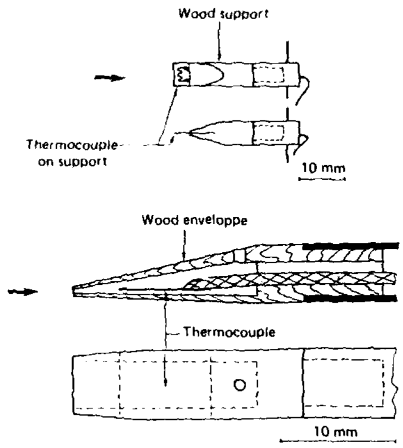


Fig. 45 - Temperature measurements in the T2.

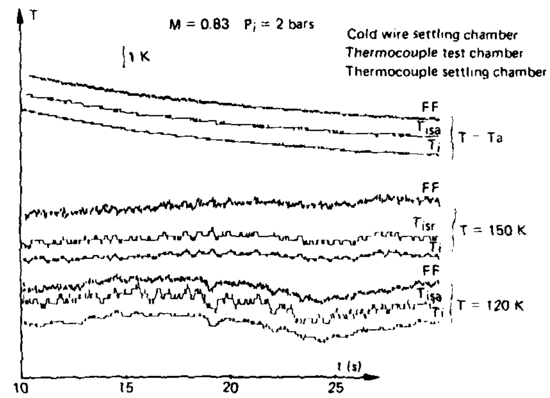


Fig. 46 - Comparison of temperature measurements in the T2.

4.3 - *Skin friction gages*

DISA hot wire or film tranducers on a balsa chip, and quartz bar gages with a shorter response time have been developed at the *CERT*.

The quartz bar is mounted on an aluminum or Invar support over a cavity 1 mm deep. The cryogenic chamber and T2 tests are encouraging, after calibration for the temperature and velocity, but the reliability under cryogenic conditions is not yet very good and improvements are being studied, in particular the choice of a better heating coefficient. These materials are used to determine model skin temperatures after qualification in tests on a flat plate (Fig. 47).

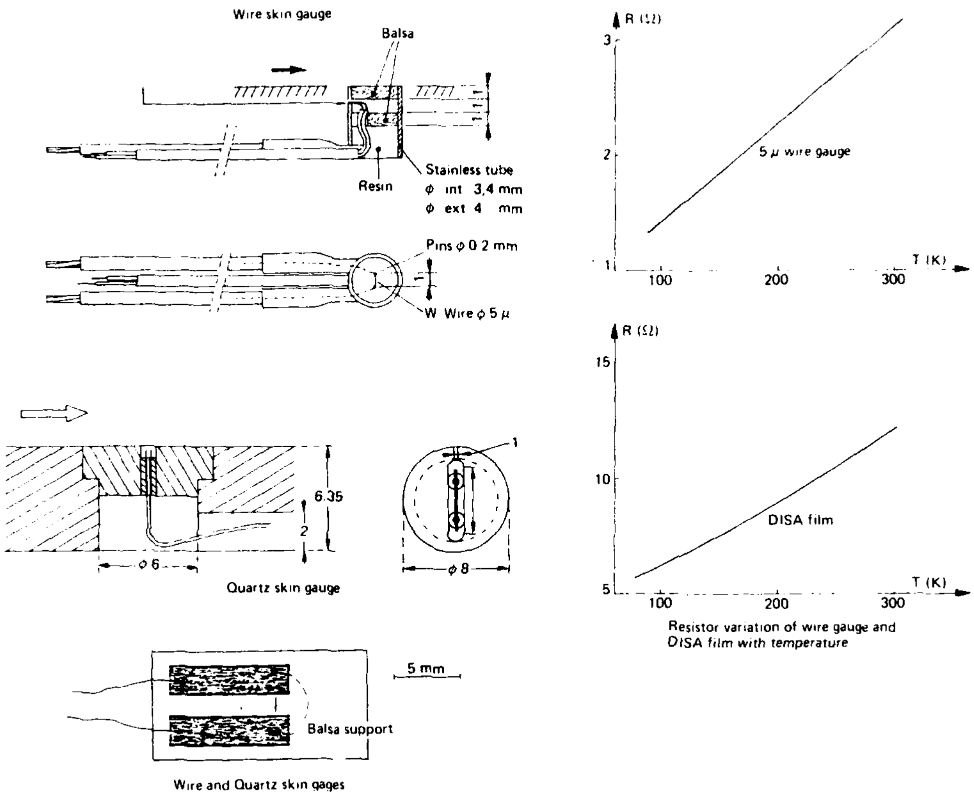


Fig. 47 - Skin temperature measurements in the T2.

5 - Attitude and Deformation measurements

We mentioned the model attitude measurement with inclinometers in the paragraph on accelerometers.

Determining the aerodynamic forces on a model in the wind-referenced axes means that the angle of attack must be known to within 1/100th of a degree, when the forces are measured with a balance-sting in the model-referenced axis system.

We often observe thermal drift in the passive (gage-type) and slaved inclinometers used in todays' noncryogenic wind tunnels, even some that are already warm-housed. We also observe zero drift due to severe dynamic exicitation, *e.g.* in the buffeting area. Finding the angle of attack by calculating the deformation of the sting line, still a common method a few years ago, does not provide the accuracy required now. With optical methods, systems external to the model can be used that are not subject to the thermal or dynamic effects mentioned above. If only because of the greater difficulty of utilization of the device, which creates tracking problems, the use of these methods may be limited to the adjustment of the inclinometers.

In a preliminary study at *ONERA* on the means used for determining the model deformation, beginning with the total wing twist, we were aiming at a measurement accuracy of the order of 0.01°. This can be obtained with the torsiometer we developed [16].

It is becoming more and more necessary to know the actual form the model takes when subjected to aerodynamic stresses, because of the increased accuracy sought in wind tunnel testing, and because of the aerodynamic forces that increase with aircraft performance, the lighter and more slender structures, the greater model instrumentation and higher dynamic pressure.

By varying the temperature in a cryogenic wind tunnel we can study the effects of varying the Reynolds number at constant dynamic pressure and thus, assuming there are no thermomechanical strains, without changing the model deformations. However, aerodynamicists would rather have a detailed knowledge of the real form of the model corresponding to their data.

5.1 - *ONERA-BBT torsiometer*

The first torsiometer prototype underwent several changes in construction to improve its reliability and avoid certain random shifts observed in pressurized wind tunnel operation. The principle of the instrument is diagrammed in figure 48. It was made more convenient to use by adding an auxiliary optical device to determine quickly the initial orientation of the target at the start of testing and the angle the polarized beam makes with the target. This information is necessary if the measurement data is to be analyzed accurately.

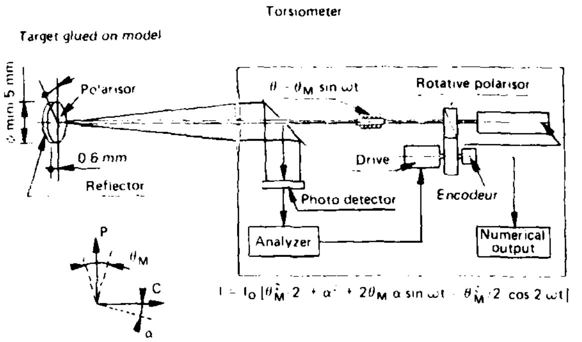


Fig. 48 - ONERA *BBT torsiometer.*

Also, by motorizing the support in elevation and azimuth, the displacement of the target with the model can be tracked, or several targets can be sighted in succession, including a fixed reference target if necessary.

The data obtained on a large half model in the S1MA wind tunnel, in transonic regime, shows that the torsiometer on its "tracking" support can be use not only to measure the torsion but also the bending of the wing (Fig. 49). This industrial test also showed that this device is capable of measuring the angle of attack with the desired precision. It should be possible to use this process in cryogenic wind tunnels.

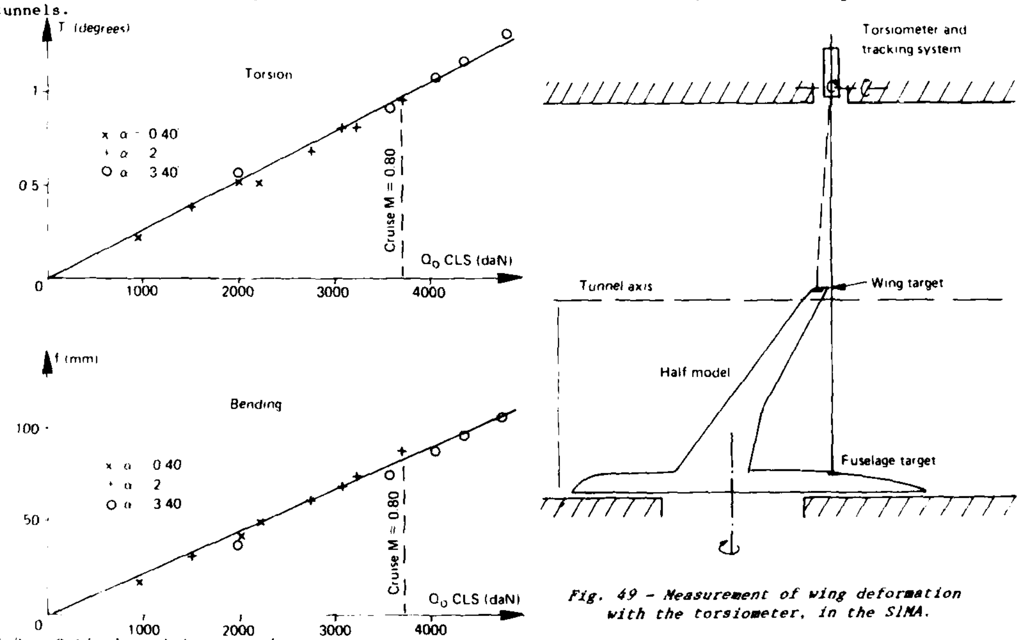


Fig. 49 - Measurement of wing deformation with the torsiometer, in the S1MA.

5.2 - *Optical position transducers*

Figure 50 shows a relatively simple measuring device for detecting the shape of the trailing edge of a wing under test. The receivers measure the displacement of lights emitting from fiber optics in the model. The system has been perfected. It measures either in two perpendicular directions or in a single direction, with double sensitivity, using four-sector receiver cells. The major disadvantage of this device, originally designed for wing bending measurements, is that it is carried by a probe that is subjected to aerodynamic forces, and the deformation of the support thus has to be corrected for.

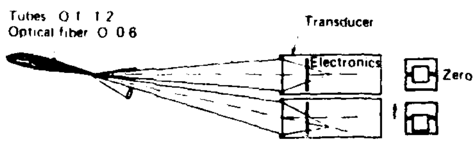


Fig. 50 - Optical position measurement.

5.3 - *Form recognition*

To determine the actual shape of the model in the wind, 20 to 50 points need to be identified on the model.

After analyzing the many possible optical methods, *ONERA* has finally adopted stereo image observation and reconstruction. The criteria of field and field depth, accuracy, speed and convenience of recording and, as a secondary consideration, the speed of the recognition, were all taken into account. Existing video cameras such as the *CCD* bar matrices, do not meet the set criteria, in particular as concerns the accuracy and scanning time. The *CERT* is currently studying an original way of breaking down the image of reference sources into two perpendicular coordinates and automatically scanning the sources, activated sequentially by a computer. A feasibility prototype has yielded encouraging results in the laboratory (Fig. 51) and the current phase of work concerns the feasibility of extrapolating the prototype to wind tunnel conditions.

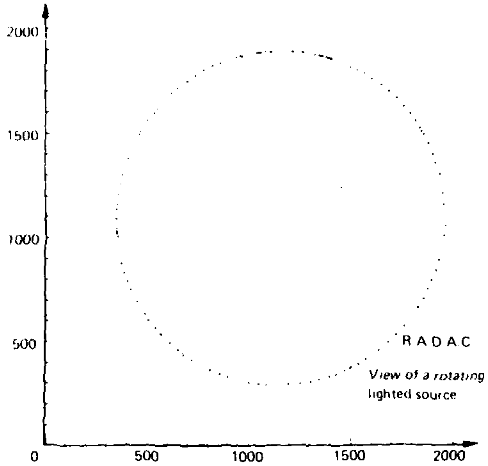


Fig. 51 - ONERA RADAC *system (being studied).*

The laboratory prototype uses a 1 mW laser diode as a source, transmitted by a 50 µm optical fiber. The emitting source is secured into a rotating arm that describes a circle. The receiver system and the minicomputer that reconstructs the image are placed some three meters from the source and can reconstitute displacement velocities up to 1 m/s without any difficulty.

6 - Model Instrumentation

6.1 - *Pressure holes*

The *DFVLR* and *ONERA* began acquiring experience in pressure hole construction when creating airfoils for 2-D flow tests [17 and 18].

To take an example, the first cryogenic model for the T2, constructed by *ONERA*'s main shop, is entirely metal. The airfoil part measures 390 mm spanwise, with a 100 mm chord. Its longitudinal section is a CAST 7 profile, already tested in various noncryogenic wind tunnels. The attachment mounting brackets are prismatic in form and are placed on either side of the airfoil part. They are very long in the spanwise direction, as this is necessitated by the cooling box. The thermocouple wires and pressure tubes come out of the model through the left hand mount.

The model is hollow, and is made of three elements: the leading edge and two-half shells welded together. This architecture is based on the heavy loads applied in a pressurized transonic wind tunnel, and on test data previously acquired on test pieces in a cryogenic chamber.

The left mounting bracket has the holes for mounting the model on the cooling system cart. The bracket on the right side has a special bar receiving the centering and locking system pin.

The pressure holes are grouped around the median plane of symmetry and are arranged in a helical pattern all around the airfoil. The 103 holes are 0.1 mm in diameter near the leading edge (32 holes) and 0.3 mm in diameter over the rest of the airfoil (71 holes). There are also 18 thermocouples, which cannot be seen from the outside, eight of which measure the temperature inside of the material and ten of which measure the temperature near the surface, in the pressure hole area.

The particularly small, unusual size of the pressure holes at the leading edge, which is justified considering the local aerodynamic conditions, was a determining factor in the choice of the machining methods and, consequently, in the choice of the materials, treatments and soldering processes.

To make 0.1 mm pressure holes with the usual geometric tolerances, a general survey of the available means and methods and various laboratory feasibility tests led the designers to adopt the individually prepared bushing, drilled and brazed in a tube and then swaged into to the model (Fig. 52). Using this method meant that the area of the airfoil carrying these 0.1 mm holes had to be machined to near-final dimensions before the pressure gages were swaged in place, and any further machining of the airfoil in this area presented the risk of shortening the bushing down to the cavity for the pressure tube.

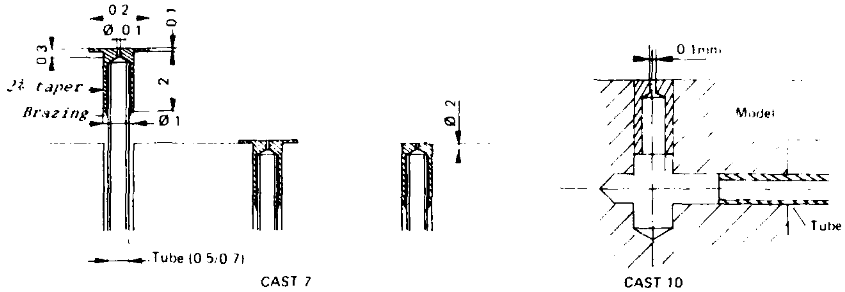


Fig. 52 - Pressure coupling for the CAST models.

The decision to machine part of the airfoil to near-final dimensions before fitting the 0.1 mm pressure couplings was considered in the choice of the material and welding proccess for the three model elements. A Marval 18 maraging steel was adapted because of its very small deformations when soldered and when heat-treated. The electron-beam welding proccess was chosen because it applies the least heat. Aside from the leading edge, the tubes connecting the 0.3 mm diameter holes to the tranducers were bonded with *CIBA-GEIGY* XF161-162 resin, which has an excellent behavior in the cold. The Marval 18 was kept in the annealed state.

The construction was simplified for the second CAST 10 airfoil. The model consisted of four electron-beam welded elements (trailing edge separated with respect to the CAST 7). Most of the 0.3 mm pressure holes were drilled directly to the model.

The 0.1 mm pressure holes on the leading edge, and certain 0.3 mm holes, were drilled into bushings. The connection tubes are no longer fastened to the bushings, but bonded to the end of the hole recieving the bushings.

The construction is thus carried out in the following sequence: machining of the four elements to near-final dimensions, drilling, installation of the tubes, welding the elements to each other, airfoil finish, drilling of the holes for the bushings, installation and removal of the bushing heads.

6.2 - *Motorization*

The model motorization was studied by *MBB* [19 and 20]. After a bibliographical study and analysis of the possible alternatives, the components (motors, reduction gears, shafts, tubes and position transducer) were tested under load in a cryogenic chamber.

Close cooperation was set up with a supplies of cryogenic dc motors different drive transmission mechanisms. Teflon was used for the new bearings, and the lifetime of the assembly is estimated at 200 hours of operation in a cryogenic environment. After 30 hours of tests, no weaknesses were apparent. The equipment is of course degreased before use.

Figure 53 shows some of the results obtained. Despite differences due to geometric variation of the components with temperature, the tested systems operate correctly with a minimum efficiency at about 150 K. This is due to the change in the behavior of the bearings. Considering these results, *MBB* feels that the components tested could be used in an ETW wind tunnel model.

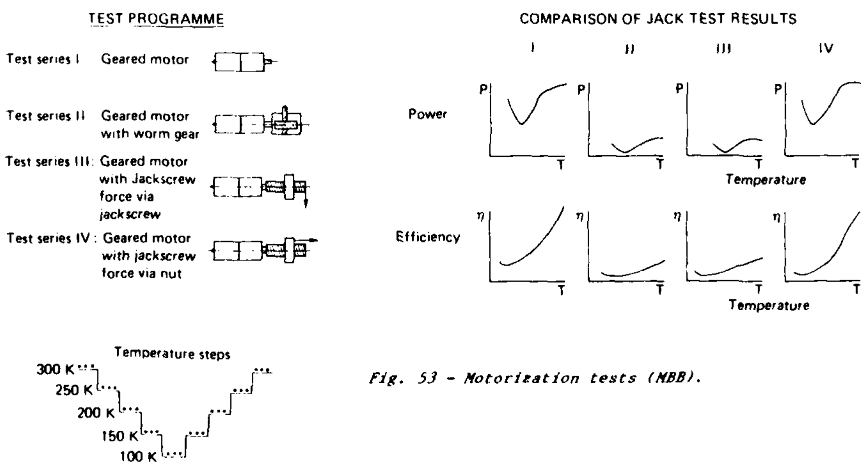


Fig. 53 - Motorization tests (MBB).

6.3 - *Robot arm*

Although robots are not fully part of wind tunnel "instrumentation" in the usual sense of the term, the first experiments in Germany on changing the configuration of a model with a robot arm show the advantage of developing motorized mechanisms that can operate in the cold. Motorized supports will also have to be planned for the wind tunnel, *e.g.* for probing the flow around or downstream of the models.

7 - CONCLUSION

The examples presented in this paper give an idea of the various actions needed to adapt conventional wind tunnel instrumentation for use in cryogenic wind tunnels.

Much data of interest has already been acquired and the effort is continuing in Europe, with a view to defining in common the best solutions for the ETW. Fruitful information exchanges between the ETW teams in Europe and NTF teams in the United States are also helping advance these techniques.

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FUNDAMENTAL REFLECTIONS ON CRYOGENIC TESTING

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ABSTRACT

This paper concerns a number of aerodynamic problems related to cryogenic testing but which can also be encountered during testing at room temperature. The first part describes the various factors involved to achieve the best similarity possible between an aircraft in flight and the model in the wind tunnel. The second part covers the analysis of these factors: effects of a non adiabatic wall, boundary layer transition, two-dimensional testing, effects of the Reynolds number. In the paper, it is attempted to alternate theoretical considerations with practical examples in order to illustrate the importance of "experimental/theoretical" correlations. Finally, the paper endeavors to highlight a few areas to which effort must be devoted in the future so that the new technique of cryogenic wind tunnels now available to scientists and manufacturers provides reliable and accurate results leading to a better analysis of aerodynamic phenomena and improved prediction and optimization of aircraft performance.

MAIN NOTATIONS

x, y, z	direction of the flow, normal to the wall, spanwise (x_1, x_2, x_3)
c, C	chord, heat capacity
C_d, C_l, C_m	drag, lift, moment coefficients
C_{dp}	pressure drag
C_f	friction coefficient
L	reference length
u, v, w	velocity
M	Mach number
ρ	density
p	pressure
μ	gas viscosity
$\gamma = C_p/C_v$	ratio of specific heats at constant pressure and volume
$\alpha = \gamma_{effective} = [\partial(\log p)/\partial(\log \rho)]S$	partial derivative at constant entropy S
$R_L = \rho u L/\mu$	Reynolds number related to L
q	dynamic pressure
T	temperature
t	time
α	angle of attack
ϕ	thermal flux
$\bar{X} = \frac{X}{X_{AW}}$ or $\frac{X}{X(R_o)}$	
δ	thickness of the boundary layer
$\delta_1 = \int_0^\delta (1 - \frac{\rho u}{\rho_e u_e})\, dy$	displacement thickness
$\delta_{1i} = \int_0^\delta (1 - \frac{u}{u_e})\, dy$	incompressible displacement thickness
$\theta = \int_0^\delta \frac{\rho u}{\rho_e u_e} (1 - \frac{u}{u_e})\, dy$	momentum thickness
$\theta_i = \int_0^\delta \frac{u}{u_e} (1 - \frac{u}{u_e})\, dy$	incompressible momentum thickness
$H = \delta_1/\theta$	shape factor
$H_i = \delta_{1i}/\theta_i$	incompressible shape factor
$T_u = \frac{\sqrt{\overline{u^2}}}{u_e}$ or $\frac{\sqrt{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}}}{\sqrt{3}\, u_e}$	turbulence intensity

Subscripts

cr	critical
e	flow external to the boundary layer
s	separation
t	total pressure nd temperature values
T	transition
∞	values at infinity
W	wall
AW	adiabatic wall
—	average value or ratio of values
R/m	Reynolds per meter
j	jet
r	roughness

Abbreviations

%	percent	‰	per thousand
2D	2-dimensional	BL	boundary layer
3D	3-dimensional	LN_2	liquid nitrogen
L.E.	leading edge	GN_2	gaseous nitrogen
T.E.	trailing edge	T.D.	fixed transition

1. INTRODUCTION

The development and use of cryogenic wind tunnels today represents a considerable progress in the area of aerodynamic testing.

It has now become possible to obtain nearly total similarity between the model in the wind tunnel and the aircraft in flight.

This new technique available to scientists and manufacturers provides reliable and accurate results allowing a better analysis of aerodynamic phenomena and improved prediction and optimization of aircraft performance (Fig. 1).

In addition, the cryogenic wind tunnel, in which the Reynolds number can be as high as that in flight, offers the enormous advantage of an independent variation of the dynamic pressure $q = 1/2\rho V^2$ and the Renolds number $R_e = \rho U\ell/\mu$ by simultaneously varying the gas temperature and pressure. It is thus possible to dissociate a number of parameters heretofore coupled, such as deformation of the model and viscous effects within a very broad domain.

However, a number of difficulties related to cryogenics and often to aerodynamics in general must not underestimated, and it is necessary to preserve a critical attitude.

Testing in a wind tunnel always involves a complex set of elements (Fig. 2): model, support, instrumentation, "wind tunnel system", computation, data processing, etc. which must be consistent and of the best quality possible.

In this paper (Fig.3) we will attempt to demonstrate that the two main parameters of similarity, i.e. the Mach number and the Reynolds number, are not sufficient. A number of other parameters must be taken into account, such as the surface condition of the model, any thermal fluxes resulting from disequilibrium of the model, the deformations (model + support), the qualities of the flow in the wind tunnel, wall effects,etc.

Another advantage of cryogenic wind tunnels is to allow aerodynamic research to be carried out for wide variations of the Reynolds number.

In the past, we were often tempted to explain a number of poorly understood phenomena by discrepancies in the reynolds number. Today, we can easily vary this parameter and systematically study the variation of certain values.

First, the Reynolds number effect can be tested in the wind tunnel by a "pressure-temperature" correlation (the same Reynolds number can be obtained at different temperature levels by varying the pressure). Second, any differences which exist between wind tunnel testing and the aircraft in flight must be explained and investigated elsewhere.

I believe this research will make it possible to achieve major progress in the field of aerodynamics in the future.

However, the immense progress achieved in the theoretical field where the development of numerical methods and modeling of complex viscous flows makes it possible to process phenomena heretofore not approached must not be neglected.

A complete flow can be computed without recourse to experimental data (ideal fluid-viscous fluid coupling method, resolution of Navier-Stokes equations) or using certain experimental data to predict other data or confirm the coherence with certain results.

Conversely, the experimental data can be used to readjust the theoretical models or to take into account a number of parameters which were initially ignored at the start of the theoretical analysis.

After these general considerations which will serve as guidelines throughout this paper, I would like to indicate that the many results presented are from publications, a number of which are given in reference and whose authors I thank and also from testing conducted in the ONERA-CERT T2 cryogenic induction tunnel in Toulouse, described more fully by J.B. DOR/ Ref. 27/ in the framework of this Lecture Series.

2. PROBLEMS RELATED TO CRYOGENIC TESTING

When it is attempted to achieve the best possible similarity between an aircraft in flight and a model in a cryogenic wind tunnel, it is important to take into account a number of parameters, as shown in the Figure 3.

In addition to conventional variables such as Reynolds number and Mach number, it appears important to analyse the real gas effect. The limits of use of the wind tunnel at low temperatures must also be specified.

A number of other parameters will be studied below, mainly the non adiabatic wall effect, the transition effect and the effect of the Reynolds number.

2.1. Real Gas Effect

An objection which arises immediately concerns the large variations in the ratio γ of specific heats as a function of temperature for nitrogen (Fig. 4).

This objection as well as many others were practically eliminated thanks to the important works conducted at NASA LANGLEY/4/ and a few works conducted by the DFVLR, the NLR, the RAE and ONERA. For this paper, we will retain only the following essential points :

If the real gas effects are studied for an isentropic flow using the best possible formulations (nitrogen characteristics given by JACOBSEN or the state equation given by BEATTIE-BRIGDEMAN) it is observed that the isentropic expansion coefficient $\alpha = \gamma_{effective} = (\partial \log p/\partial \log \rho)_s$ remains very close to 1.4 (Fig. 4) for a wide range of pressures and temperatures: $P_t < 6$ bars and $T > T$(saturation).

It is observed that these differences can be considered as negligible. Similar computations made for the PRANDTL-MAYER expansion and for normal shock demonstrated the same small differences.

The studies also show that the gas used can be nitrogen or air. In both cases, the real gas effects are negligible providing they are compared with an ideal gas preserving a constant γ of 1.4.

An example of isentropic expansion from reference 4 is given in the Figure 5, showing the ratio P/P_T of the real gas to the ideal gas. The expansion corresponds to M = 1.5 and uses the state equation of BEATTIE-BRIDGEMAN for both nitrogen and air.

Many tests, conducted in T.C.T., T2 cryogenic wind tunnels, etc. show excellent correlation according as the same Reynolds number is obtained by increasing the pressure or decreasing the temperature.

Other tests and computations were made for viscous flows: boundary layer, separated flow, shock wave-boundary layer interaction, etc. and also showed small differences between the ideal gas and real gas effects.

2.2. Minimum Operating Temperature Limit for Cryogenic Wind Tunnels

As concerns the operating limit at low temperatures, it seems to be related to appearance of the liquid phase in the test section. However, a distinction can be made between two types of condensation.

The first corresponds to homogeneous condensation which occurs during sudden expansions in regions at high Mach numbers. In this case, a sort of subcooling corresponding to the gas response time takes place. The temperature may then drop 5 to 10 K below the equilibrium curve.

The second process, called heterogeneous condensation, occurs when particles preexist in the flow. These particles then initiate creation and growth of droplets and eliminate any delay phenomenon.

It seems to be this second process which determines the minimum operating temperature by appearance of the liquid phase in the flow upstream of the model /Ref. 4, 27/.

3. BRIEF DESCRIPTION OF THE T2 WIND TUNNEL AND TEST TECHNIQUES USED

The T2 transonic induction tunnel, described in detail in References 5,18,20-28, was installed in the Centre d'Etudes et de Recherches of Toulouse in 1975. It was converted to operate in cryogenic state in 1981.

Many of the results described below were obtained in this wind tunnel, as well as from all the systems which were developed therein.

3.1. Description of the Circuit

The T2 wind tunnel operates by induction (Fig.6). Its range of operation covers:

Mach number:	0.3 to 0.9
Pressure:	1 to 5 bars
Temperature:	100 to 300 K
Run time:	30 to 100 seconds
Reynolds number:	3 to 40 million
(for C = 200 mm)	

The test section is equipped with flexible walls making it possible to adapt the walls by three or four iterations and probe the wake during the run. Most of the tests concern airfoil profiles, but threedimensional setups can also be made.

The Mach number is regulated by a throat downstream of the test section for $M > 0.6$.

The flow is produced by an induction system consisting of compressed air jets, located at the trailing edge of the seven vanes of the first corner ($M_j = 1.6$; $P_{ij}/P_{tTS} \approx 3$ to 4; $Q_{TS}/Q_j = 6$ to 10).

Liquid nitrogen is injected at the wall downstream of the first corner by 32 nozzles with staggered flow rates, forming a sort of digital valve ($Q_{LN2}/Q_{TS} \approx 7\%$ at $T_t = 100$ K).

The exhaust is performed through porous walls between the test section and the first motor corner. The exhaust flow rate is controlled by seven digital valves.

The entire circuit, made of ordinary steel, is internally insulated by a thin layer of insulation 5 to 10 mm thick.

3.2. Execution of a Cryogenic Test

The entire run is controlled by a first computer, with the wall measurements and adaptation controlled simultaneously by a second computer(Fig.6).

The Figure 7 shows a typical run carried out with precooling of the model. It includes four phases:

1) Stabilizing of the temperature selected at a low Mach number ($M \approx 0.3$) and a low pressure ($P_t \approx 1.1$b).
2) Insertion of the precooled model in the test section and locking in place of the model.
3) Obtaining of the Mach number and pressure, preserving a constant temperature level.
4) Regulation phase.

The walls are adapted during the stabilized phase by an iterative process requiring three or four iterations, each lasting approximately 7 seconds.

This process uses the distribution of the velocities measured on the walls as well as their forms, with converging to the "infinite atmosphere" case achieved by a linearized computation supplementing the real flow in the tunnel by a virtual flow extending from the walls to infinity /Ref. 25, 26, 28/.

3.3. Models Used in T2

Figure 8 shows schematic diagram of the CAST 7 and CAST 10 airfoil profiles used in the T2 wind tunnel. It should be noted that the two profiles include 103 pressure taps, which have a diameter of 0.1 mm in the leading edge area (0.3 mm elsewhere).

The models are also equipped with thermocouples. In particular, the CAST 10 profile includes an area 40 mm wide by 3 mm thick designed to study the model temperature stabilization.

3.4. Qualities of the Flow in the T2 Wind Tunnel

The main characteristics of the flow were qualified both at room temperature and at cryogenic temperatures /Ref. 27/. The main results are summarized below.

- the turbulence intensity $\frac{\sqrt{\overline{u'^2}}}{u_e}$ is in the neighborhood of one thousandth.
- the pressure fluctuation level on the test section wall corresponds roughly to the noise of the turbulent boundary layers on the walls.
- the transverse thermal gradients are below $\pm$ 0.3 K for the center part of the test section.
- the temperature fluctuations are in the neighborhood of $\pm$ 0.15 K at $T_t = 120$ K and $\pm$ 0.03 K at room temperature.

4. EFFECTS OF A NON ADIABATIC MODEL WALL

4.1. Initial Approach in the Case of a Laminar Boundary Layer on a Flat Plate

Analyzing the development of a laminar boundary layer of very small initial thickness located in a flow with a constant Mach number of M = 1.2 computed by a finite volume method (*) makes it possible to observe the following phenomena when the wall temperature is varied (Fig.9):

- the variation in the displacement thickness δ_1 is parabolic as a function of the abscissa (as appears in the initial equations for $\delta = 0$). In addition, this thickness increases when the wall is heated.
- the variation in the momentum thickness θ is identical to that of δ_1 as a function of the abscissa but is not particularly sensitive to the wall temperature.

There is a decrease in the local skin friction coefficient C_f and a low sensitivity of this coefficient as a function of T_W/T_{AW}. This result is also given by the relation $C_f/2 = d\theta/dx$.

The wall temperature effect is illustrated in the Figure 10 where the variation in the integral values of the boundary layer: δ_1, δ_{1i}, θ, θ_i and the friction coefficient C_f as well as the form parameters H and H_i are plotted for a fixed abscissa.

In this figure, the various values are related to the adiabatic values noted AW for $R_x = 2$ and 10 million. For a hot wall, a substantial increase in H and δ_1 is observed, a more moderate increase in δ_{1i} and θ_i whereas H_i varies only by 1 percent. On the other hand, θ and C_f decrease very slightly, by approximately 0.5 percent.

The wall temperature effect can be compared with the Reynolds number effect for an adiabatic wall (Fig 11). According to the boundary layer equations, all variables δ_1, δ_{1i}, θ, θ_i, C_f vary as $1/\sqrt{R_x}$, which means that H and H_i remain constant.

There is also an enormous variation in the integral and friction values, divided by $\sqrt{2} = 1.414$ when the Reynolds number is multiplied by 2.

4.2. Computation of Temperature Stabilization on a Flat Plate Initially Hot in the Front Part

The example of the Figure 12 illustrates an important phenomenon which occurs during temperature stabilization of a model initially in thermal disequilibrium.

The computation is made by coupling between a finite volume method for the laminar boundary layer and a plate representing a thermal inertia. The plate is assumed made of blocks each at a uniform temperature $T_W(x_i)$ exchanging fluxes only with the boundary layer.

The case analyzed corresponds to $M = 0.1$, $P_t = 1$ b, $T_t = 273.2$ K. The thermal inertia involves the term $(\rho\ Ce)_{metal} = 1000$.

The figure 12 shows the longitudinal temperature distribution at different times on the left side and the flux distribution on the right side.

The first observation is the rapid variation in temperature near the origin where the boundary layer is thin and creates substantial fluxes, but even more important is the temperature rise and fall downstream of the plate ($x/c > 0.5$) related to the thermal convection of the boundary layer.

This example illustrates the precautions required to compute a transient when longitudinal wall temperature gradients exist. In particular, the phenomenon observed would not appear using a formulation based on introduction of the heat transfer coefficient h and the adiabatic equilibrium temperature T_{AW} to compute wall fluxes $\phi_W = (T_W - T_{AW})\ h$.

4.3. Case of a Turbulent Boundary layer on a Flat Plate

A computation case corresponding to $M = 1.2$, $T = 120$ K, $P_t = 2$ bars is illustrated in the Figure 13 where the variation of δ_1, θ, C_f is plotted versus the abscissa for three wall temperatures.

The finite volume method applied uses a mixing length concept developed at the DERAT (*).

A much more linear variation in δ_1 and θ versus the abscissa is noticed immediately as well as the relatively low decrease in the friction coefficient, with a value substantially above that of the laminar case.

When the wall is heated, all the parameters are affected: δ_1 increases, θ and C_f decrease.

The wall temperature effect on the boundary layer parameters is illustrated in the Figure 14. As for the laminar case, all the values are related to the adiabatic values for $R_X = 20$ and 100 million.

For a hot wall, a considerable increase in H and δ_1 is observed whereas θ and C_f decrease by approximately 3.5 percent. However, the incompressible shape factor H_i remains practically constant.

The wall temperature effect can be compared with the Reynolds number effect for an adiabatic wall (Fig. 15).

In this case, it can be noted that the decrease in the shape factors H and H_i of the boundary layer is very small, approximately 1 percent, when the Reynolds number is doubled, with a decrease of approximately 10 percent in the other values.

In conclusion, as for the laminar case, a hot wall thickens the boundary layer. As the friction of the boundary layer is decreased, it tends to separate earlier in the areas of the profile where the velocity gradient is negative. Several differences in sensitivity between a laminar and a turbulent boundary layer are also noted, both as a function of T_W/T_{AW} and of the Reynolds number.

(*) The programs used were developed by B. AUPOIX.

4.4. Effect of a Non adiabatic Wall on the Transition

The effect of this parameter, which has been experimentally demonstrated for a number of years, leads to an earlier transition when the wall is heated.

This tendency of the laminar boundary layer to become unstabilized was approached theoretically in spite of considerable difficulties. The Figure 16, from reference 35, illustrates this effect.

As will be seen in the section on transition, disturbances develop and become amplified in the laminar boundary layer until turbulence occurs.

A conventionnal criterion, often retained, consists of stating that the transition Reynolds number corresponds to a disturbance amplified by a factor e^9 /Ref. 15/.

The authors plotted this curve, shown in the Figure 16, which also shows another formulation resulting from flight-wind tunnel correlations /Ref. 6, 10, 35/: $R_T/R_{TAW} = (T_W/T_{AW})^{-7}$. In both cases, it can be concluded that the location of the transition is very sensitive to the wall temperature since a variation of 1 percent in T_W/T_{AW} is equivalent to a variation of 4 to 7 percent in the transition Reynolds number.

However, attention must be drawn to the extreme experimental and theoretical difficulty in presence of a thermal drift (Sec.4.2.) where longitudinal gradients occur naturally. It would seem that only a coupled "boundary layer-model heat transfer" computation could account for these phenomena.

4.5. Experimental Examples of Non Adiabatic Wall Effects

The first example, drawn from the theoretical study conducted at NASA LANGLEY /Ref. 9/, concerns the stablization time of models subjected to rapid variation in the total temperature of the flow, from 165 to 115 K (dynamic range provided by the NTF wind tunnel: $\Delta T = 50$ K).

Two important points were revealed by this study.

For the case considered in the Figure 17, a precision of 8 percent on the temperature appears to be sufficient so as not to result in an error above $\pm$ 0.0001 on the drag coefficient C_d.

In addition, the time required to reach equilibrium may be very long. A good solution consists of using hollow models as shown in the Figure 18.

Another experimental illustration of this solution is given in the Figure 19, showing the temperature variation on an element of the CAST 10 profile (tests in the T2 wind tunnel) in an area where the wall thickness is 3 mm.

A second example drawn from the study conducted by DOUGLAS Corp. /Ref. 6 to 8/ also stresses the importance of the wall temperature effects.

The authors contribute a large amount of experimental data on airfoil profiles. The sensitivity to temperature is particularly high in the case of a free transition which can move on the abscissa as well as in cases of shock wave-boundary layer interaction in the vicinity of appearance of a separation (buffeting limit). The same is true when the separation progresses.

It also appears that the variation in characteristic values such as C_l and C_d may not be linear as a function of T_W/T_{AW} as occurs in the case illustrated in the Figure 20.

In conclusion, the authors feel that an accuracy of about one percent on the wall temperature is necessary in many cases and that the non adiabatic wall effects must also be taken into account for flight testing.

The last examples given concern tests conducted in the T2 wind tunnel.

An initial analysis was made at room temperature with the CAST 7 profile initially heated before the run /Ref. 21 and 31/.

The main result is illustrated in the Figure 21 for a test conducted at M = 0.76, α = 0 , tripped transition at 7%, allowing the profile to vary towards thermal equilibrium during a long run, measuring the pressure and temperature distribution of the model at midsection.

The result obtained is compared to a coupled computation (computation with complete potential equation plus boundary layer). The coherence of the results appears satisfactory and shows a strong variation in C_l and C_m, but not in the drag. A sort of compensation occurs between the friction drag which decreases and the pressure drag which increases in connection with the increase of ξ_1.

A second analysis (Fig.22) was made at room temperature with the CAST 10 profile with a free transition, in a case where the transition location could be observed. This location is identified by a disturbance which occurs in distribution of the Mach number, both on the lower surface where oil visualizations showed a practically fixed separation bubble and on the upper surface where a free transition occurred in an area where the Mach number was roughly equal to 1. Visualizations as well as the temperature variation of the model and the computation demonstrated the correlation between the location given by the bump in the Mach number distribution and the transition (see Section 5).

In the figure 23, the variation of the transition abscissa, identified by the start and end of the bump, is plotted as a function of the average profile temperature. The large variation of this transition abscissa versus the T_W/T_{AW} ratio can be observed.

The same figure also shows the variations in lift and drag. Drag, in this particular case, is relatively insensitive to the temperature ratio.

The movement of the transition was compared with the Reynolds number effect in this specific case where there is a negative velocity gradient between 20 percent 50 percent of the chord. A formula of the type R_T [illegible] appears to give a good approximation of the phenomenon (Figs. 36 and 37).

5. PROBLEMS RELATED TO TRANSITION OF THE BOUNDARY LAYER

5.1. First [illegible] Approach to Free Transition on a Flat Plate with an Incompressible Flow

In order to gain a good understanding of how the transition occurs /Ref. 11 to 17/, it is of use to correctly analyse the fundamental aspects relative to a boundary layer on a flat plate (ideal surface condition, thermal equilibrium, low level of turbulence external to the boundary layer).

The boundary layer, initially laminar and stable, has the property of amplifying the disturbances above a certain critical abscissa x_{cr} (Fig. 24).

The disturbance waves, often called "TOLLMIEN- SCHLICHTING waves", progressively increase in amplitude for a well defined frequency domain and degenerate into turbulence after a highly complex, non linear transient phase called transition. The theoretical approach of this phenomenon is by the linear stability theory introducing a disturbance term of the type $\psi(x,y,t) = (y)\, e^{-\alpha_i x}\, e^{i(\alpha_r x - \omega t)}$ in the NAVIER-STOKES equations, giving the ORR-SOMMERFELD equation. This equation is used to determine the amplification coefficients and the frequency domain concerned.

This method leads to results approaching the experimental results when including the total amplification rate $A/A_0 = \exp\left(\int_{x_0}^{x} -\alpha_i\, dx\right)$ for each unstable frequency. It is observed that when an amplification in the neighborhood of e^9 [illegible] is taken for the most unstable frequency, this approximately yields the experimentally observed transition location.

In order to gain a good understanding of the role played by transition on the drag of a plate (C_d = [illegible]), the Figure 24 shows the variation of C_d versus the Reynolds number for two possible configurations /Ref. 16/.

The first configuration consists of setting the transition at a given percentage. A decrease in the drag with the Reynolds number is then observed since, as was seen in Section 4, the increase in the Reynolds number decreases the friction and therefore the momentum thickness.

However, if the location of the transition, assumed sudden, varies preserving a constant transition Reynolds number R_{XT} as will be seen below, R_{XT} is related to the turbulence level), the following phenomena are observed :

. if $R_c < R_{XT}$, the entire boundary layer is laminar and the variation is along the low 100 percent curve

. if $R_c > R_{XT}$, there is first an increase in the drag, due to rapid progression of the transition towards the leading edge, which overrides the gain achieved on each boundary layer taken separately. It is only when the transition reaches x/c = 20 percent of the chord that the increase stops and a decrease tending asymptotically to the 100 percent turbulent curve is observed. It can also be seen that the maximum drag takes place for a Reynolds number R_c between 10 and 40 million when the transition Reynolds number is close to the conventional value of 3 million.

5.2. Two-Dimensional Criterion Developed at DERAT

A transition criterion was proposed by DERAT /Ref.12 and 13/ from the instability theory. An initial semi-empirical formulation simple to apply relates the variation in the Reynolds number of the momentum thickness computed from the critical Reynolds number to a function cumulating the effects of the pressure gradient $\bar{\Lambda}_{2T}$ and the external turbulence Tu (Fig. 25). This criterion gives the start of transition abscissa X_T. The transition as such must then be computed . To do so, an intermittence is assumed (with the boundary layer alternately turbulent and laminar in a given point). The intermittence function γ is a function of θ/θ_T, starting at 0 for $\theta = \theta_T$ and tending towards 1 as θ increases to 2 θ_T.

A second formulation of the same criterion which can handle more complex cases (stagnation line on the leading edge) was then established. This technique integrates the amplification rate of the unstable frequencies according to x and for each value, searches for the total amplification n of the most unstable frequency. The transition takes place when n reaches a value related to the external turbulence level.

This method was first applied to conventional 2D cases and gives comparable results. In addition, it can be used to define the transition on a stagnation line and, for a swept cylinder, gives a transition for $R_\theta > 250$, with the transition point approaching the origin of the cylinder as R_θ increases.

The transition can also occur after a separation, giving what are known as separation bubbles. The boundary layer is often reattachedback of the bubbles in turbulent form. The computation remains possible but requires processing of the local coupling with the potential flow.

5.3. Influence of the Surface Condition

The influence of the model surface condition is capital for transition phenomenon, all the more so because cryogenic wind tunnels achieve high unit Reynolds numbers. In effect, the roughness dimension must be related to a laminar boundary layer thickness parameter which decreases rapidly with the Reynolds number.

A few essential points are summarized below:

- if the roughness has the shape of a sphere with diameter k, it is considered that the transition occurs suddenly on it when $R_K = U_K K/\nu$ reaches 500 to 600 (U_K: velocity in the laminar boundary at height k).
- if the roughness is an overthickness with height k, perpendicular to the flow (cylindrical wire, strip of carborundum, etc.), the main parameter appears to be K/δ_1. The diagram of the Figure 26 illustrates the tripping limit in the case of a flat plate. In the leading edge area of a profile, δ_1 is often in the neighborhood of 0.01 to 0.02 mm and the value of k is roughly equal to it /Ref.33/.
- the case of a distributed roughness of the grain of sand type is also illustrated in the Figure 26 for a wind tunnel where the turbulence level reaches 1 ‰ . It then appears that a distributed roughness where $U_e k/\nu$ reaches 100 to 120 alters the transition location. Applied to cryogenics for P_t = 2 b, T_t = 120 K , M = 1.2 corresponding to R/m = 110×10^6, the critical roughness height is 1 µm.
- the case of holes was also studied and particularly concerns the risk of tripping by pressure taps /Ref. 32/.It seems that tripping occurs if $d/\delta_1 < 20$, where d is the diameter of the hole.

5.4. Experimental Techniques Developed to Qualify Transition

A technique supplementing that already presented (oil visualization at room temperature, discontinuities in velocity distribution), was suggested by the use of thermocouples (Fig. 27). If a small thermal disequilibrium of the model is produced at an initial time, this disequilibrium naturally tends towards equilibrium as a function of the surface fluxes, which differ greatly for laminar and turbulent boundary layers. The formation of a sort of relatively steep front is then observed on the longitudinal temperature distribution, which corresponds to the transition.

The transition location can also be investigated indirectly by probing the wake, as illustrated in the Figure 28. In this figure, two types of shock wave-boundary layer interactions can be compared: one laminar characterized by a velocity plateau shifted upstream of the shock wave, corresponding to separation then to transition of the boundary layer and the other turbulent.

The forms of the total pressure probings are very different, as the laminar interaction causes doubling of the shock wave, which takes on the form of a lambda, decreasing the total pressure loss near the profile.

In addition, there are many other methods available to qualify transition: infrared thermography (difficult to use in cryogenics), total pressure probe moved longitudinally on the wall /Ref. 10/, wall flux measurement gage, friction measurement gage, measurement of unsteady static pressure on the wall.

5.5. Transition for 3D Flows

Other types of transition can exist in addition to the instability explained above, corresponding to the longitudinal profile of the boundary layer.

5.5.1. Leading Edge Transition (Fig. 29)

As was seen above, the transition on the leading edge of a swept wing can be predicted by a 2D criterion.

The boundary layer becomes turbulent when R_θ exceeds 250. However, caution must be exercised since this computation is derived from the linear theory of stability and the disturbances are thus assumed to be small. If they become large, as is the case for the wing root, which is in contact with the turbulent boundary layer of the fuselage, contamination can occur /Ref. 7,8,13,14/. The critical Reynolds number R_θ then decreases suddenly to 100-120. This contamination seems to extend along the entire airfoil whenever the Reynolds number R_θ at the wing root becomes greater than 120.

5.5.2. Transition Due to Transverse Instability

When transition was not tripped on the leading edge, another transition mode can exist, due to the instability of the transverse velocity profile (Fig. 29).

For the transverse instability, two criteria were developed at DERAT:

- the first empirical criterion states that transition by transverse instability occurs when $R_{\delta 2} = 1/\nu \int_0^\delta W dy$ (W: transverse velocity) reaches a value (between 50 and 150) which is a function of the longitudinal profile form parameter (Fig.30).

- another criterion is based on stability computations. The velocity profile is projected in various directions normal to the wall, seeking the direction ε_{min} which gives the most unstable profile, this direction forming an angle of 1 to 4 degrees with respect to the transverse flow. The transition criterion is then obtained by empirically correlating the Reynolds number $R_{\delta 1}$ formed with the velocity profile displacement thickness projected in direction ε_{min} and the longitudinal profile shape factor H. The curves are graduated according to the turbulence level Tu. As the initial transition abscissa is known, the transition itself is computed by a conventional intermittence model.

5.6. 2D Transition Tripping Technique

As the influence of surface roughness was analyzed in Section 5.3., only the case of transition tripping by a carborundum strip is described below /Ref. 33/.

For a typical Mach number distribution, the Figure 31 shows the appropriate roughness height h_j required to fix the transition as a function of the Reynolds number and the position ($h_j \sim \delta_1$). The next figure (Fig. 32) shows the risk of overtripping which exists when the Reynolds number is increased without changing the roughness. The overthickening $\Delta\theta$ due to tripping is expressed :
$\Delta\theta = 1/2\, C_d k\, (U_k/U_e)^2$, with $C_d = 0.5$. On this figure is plotted the momentum thickness θ_{TE} computed at the trailing edge, related to the drag as a function of the Reynolds number. It is observed that if the roughness set at x/c = 7 percent and a height $h_r = 0.036$ mm, adapted for a Reynolds number of 4.5×10^6 is preserved, the error on θ may be as high as 2 percent.

However, adjusting the height for $R_c = 20 \times 10^6$ reduces the error by a factor of approximately 4.

5.7. Experimental Examples of the Transition Movement in the T2 Wind Tunnel : "Experiment-Computation" Comparison

The Figure 33 is a simple illustration of the influence of the external turbulence level Tu on the transition. A transition near 45 percent of the chord is observed experimentally by oil visualization and from the Mach number distribution. The computation correctly restitutes this location when the turbulence level Tu is 1‰ and shows the very high sensitivity of the phenomenon to this parameter. On the lower surface, the laminar boundary layer separates at about 60 percent of the chord, and the transition takes place in a separation bubble.

The Figure 34 explains the Mach number bump phenomenon by computation. This phenomenon is related to the abscissa variation of the displacement thickness δ_1. The shape factor H_i varies from a laminar value of 2.6 to a turbulent value of 1.4.

The set of transition variations for various cases as a function of angle α is illustrated in the Figure 35, which again illustrates the fact that the transition location is predicted by computation when Tu is in the neighborhood of 1‰. The form of curve 3 is not real but is due to the fact that a velocity distribution exhibiting a bump and a tendency to slightly fix transition was imposed for computation. In addition, it is observed that the laminar boundary layer can exhibit separations either towards 25 percent of the chord, area where the velocity sharply decreases, or towards 70 percent of the chord , area of negative gradient at the rear.

The figure 36 shows the variation of the transition as a function of the Reynolds number for the case $\alpha = -0.25°$, M = 0.73. Many phenomena, already described, occur when the Reynolds number increases :

- earlier transition on the upper surface
- substantial ideal fluid-viscous fluid coupling
- existence of a separation bubble on the lower surface for $R_c = 3.9 \times 10^6$ then disappearance of the bubble as transition occurs in the boundary layer without separation.

The corresponding variations of aerodynamic coefficients C_d and C_l are illustrated in the next figure (37) and represent the complexity of the phenomena.

The Figure 38 illustrates the effect of the tripping location on curve C_l (R_c) in a case where the transition is fixed.

It is probable that if the roughness is set at x/c = 7% percent, spurious tripping may occur upstream when the Reynolds number exceeds 4×10^6, which would explain the corresponding decrease in lift. This undue tripping also occurs on the free transition curve for the same Reynolds number but it is probably due to increasingly numerous spurious trippings distributed along the span of the airfoil profile.

6. EFFECTS OF THE REYNOLDS NUMBER IN A 2D CASE: CAST 10 PROFILE, M = 0.765 IN THE T2 WIND TUNNEL WITH SELF-ADAPTING WALLS

In this paragraph, a number of results obtained on the CAST 10 profile with free transition as a function of the Reynolds number are analyzed.

The figure 39 shows the characteristics $C_l(\alpha)$ and $C_l(C_d)$ for two Reynolds *numbers* : 4 and 20 million. In the case of the lowest Reynolds number, laminar areas exist *on the upper* and lower surface of the profile and vary in complex fashion as a function of the angle of attack, causing non linear variations in the aerodynamic coefficients.

It is also observed that the minimum drag occurs for an angle approaching 0 degree , corresponding to transitions on the upper and lower surfaces close to $x/c \simeq 60$ percent.

The phenomena are very different for a Reynolds number of 20 million; curve C_l (α) *becomes* linear up to around $C_{l_{max}}$ and is shifted downwards. Correlatively, the profile drag is larger, probably correspon*ding to* transition locations *very far forward*.

In the *Figures* 40 and 41, it was attempted to analyze as well as possible as a function of the Reynolds *number the phenomena* which*occurred* for a case where the shock wave drag was low: $M = 0.765$, $\alpha = 0.25$ degree .

If the displacement thickness is computed for the lower surface and upper surface boundary layers as a *function of* the Reynolds number, using in each case the experimental distribution of the measured Mach numbers and the transition criterion given in Section 5, the following *phenomena* are observed:

- *On the lower surface*, the Mach number distribution varies with the Reynolds number and the computation first indicates a separation bubble, visible in the Mach number distribution, then a transition without separation located after the maximum velocity and finally a transition at $x/c \simeq 1$ percent caused by the overspeed peak. This variation corresponds to a *variation of* θ_{TE} *indicated* by the solid line. The dashed line curves are computed by setting the transition either at $x/c = 1$ percent or at the separation point which occurs near 50 percent of the chord under the effect of the negative velocity gradient.
- On the upper surface, the Mach number distribution also varies as a function of the Reynolds number. There is first a shock wave-laminar boundary layer *interaction with a lambda form* (separation characterized by a bump followed by a plateau), then the transition *progresses* upstream of the shock wave and the interaction changes form as was illustrated in the Figure 28.
- Concerning the variation in θ_u on the trailing edge, a decrease in θ_u is observed as long as the transition is fixed by the shock wave, followed by a sort of plateau corresponding to progression of the transition. This phenomenon is identical to that described in paragraph 5.1. (Fig. 24).

Finally, a comparison between the drag measured from the wake and *the predictable* variation in the drag is plotted in the Figure 41, assuming the drag to be *proportionnal* to $\theta_u + \theta_L$ (it is recalled that a SQUIRE-YOUNG type formulation is linear :

$$C_d = 2\,\frac{\theta_\infty}{c}\text{, where } \theta_\infty = \theta_{TE}\,\frac{\rho_{TE}}{\rho_\infty}\left(\frac{U_{TE}}{U_\infty}\right)^{(H+5)/2}$$, where H is a shape factor at the trailing edge).

The value $K = 0.83$ was selected *to correspond to the* first experimental point at $R_c = 4$ million. [illegible] value probably slightly increases due to the fact that the trailing edge velocity increases with th[illegible] nolds number. However, *a probable* cross-hatched domain can be plotted for variation in the drag.

Initially, the experimental points effectively *yield* the same variation as the computation for [illegible] < 1[illegible] million, but an excessive increase in drag is then observed with respect to the computation. Thi[illegible]ase can *only be explained* by holding the leading edge transition fixed in the computation.

The analysis of these results and *many* others is being continued in conjunction with the Départ[illegible]t de Calcul Aérodynamique of ONERA. Additional information will be contributed by testing w[illegible]h fixed [illegible]n-sition, but it is already likely that the model surface condition is not sufficient, in [illegible]te of the [illegible] *number of precautions* taken. It is also of use to analyze the effect of the boundary layer-ideal flu[illegible] coupling with transition.

7. CONCLUSION

In conclusion, we will *return* to the ideas set forth in the beginning of the paper to see what we can ex*pect from the future.*

After an initial phase devoted to design and development of cryogenic wind tunnels, many facilities have already started, are starting, or are going to start the operational phase. The conclusion is drawn with this outlook, asking how to make the best possible use of the enormous possibilities offered by cryogenics.

First,the user should be warned that the Reynolds number is not the miracle parameter guaranteeing validity of the results.

More than ever, it is *necessary* to preserve a critical attitude and consider the wind tunnel as a tool (*Fig. 1, 2, 3*) to understand and analyze phenomena, simulate flows, validate new *concepts and assist manu*facturers in developing and optimizing aircraft.

However, like any tool, it has limits which must be well mastered, concerning its scope of use and taking into account all the parameters which can modify the results, one of the objectives being also to increase its efficiency.

This *paper described* the importance of many parameters, including the non adiabatic wall effects, as well as a certain number of parameters, such as surface roughness and the external turbulence level, which directly affect transition or the development of the boundary layers. In addition, the effect of the Reynolds number is often complex and gives results which, although unexpected, often have a physical explanation. From this standpoint, *all the links existing between theoreticians*, manufacturers and researchers should be strengthened.

To be efficient, the *cryogenic* wind tunnel *must* also *offer* maximum flexibility in spite of the complexibility of the tests which can be conducted in it.

An *important effort* must be made in this area. In particular, it is of prime importance to develop performing instrumentation to take into account all the essential test parameters (Fig. 42).

It is by the conjunction of many efforts in these areas that cryogenic wind tunnel testing will occupy an increasingly large place in future test facilities.

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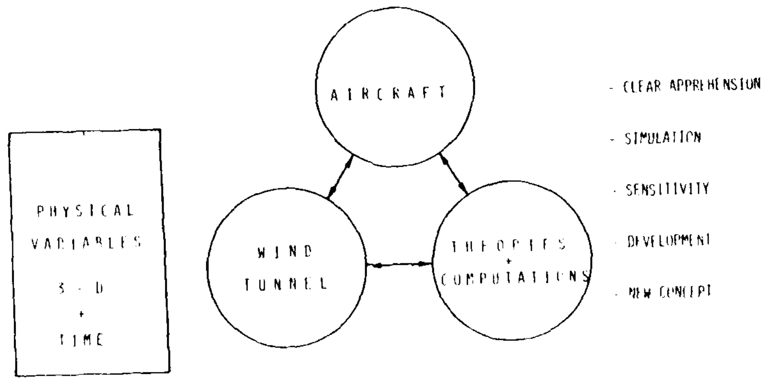


Fig. 1 - General scheme on wind tunnel part

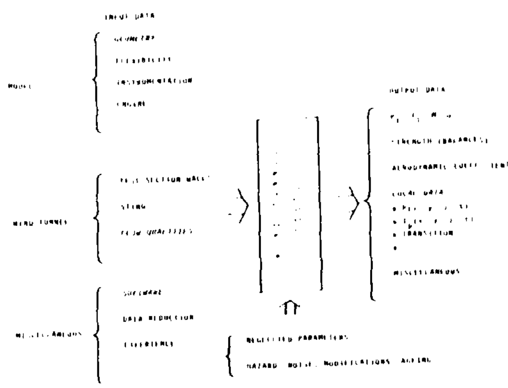


Fig. 2 - Wind tunnel "job" and concerned variables

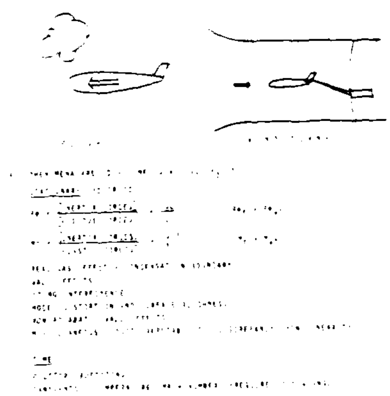


Fig. 3 - Problems involved in cryogenic testing

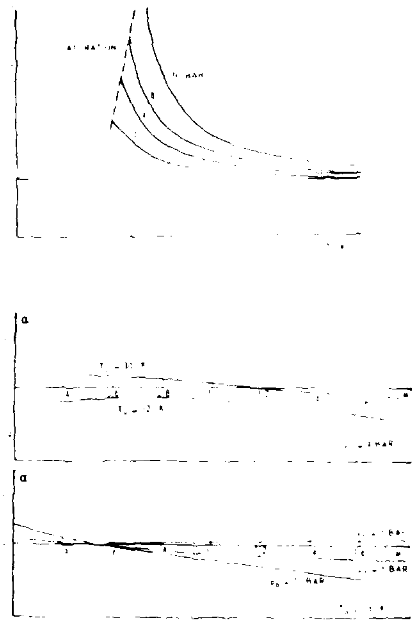


Fig. 4 - Real gas effects on γ and α
(∂ log p / ∂ log ρ) S

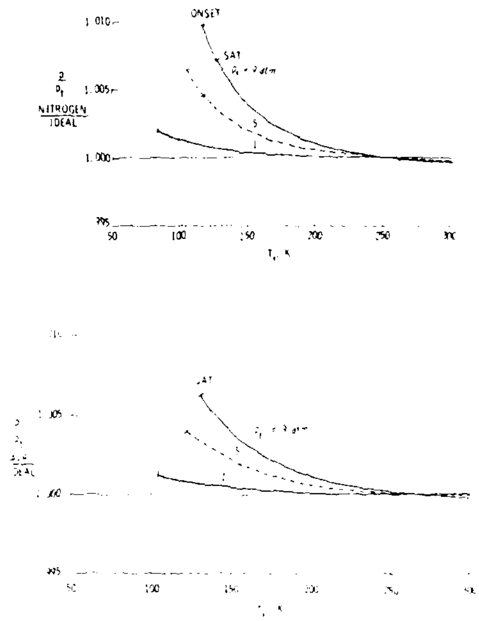


Fig. 5 - Isentropic expansion to M = 1,5 using B.B. equations of state for GN_2 and air from R.M. HALL

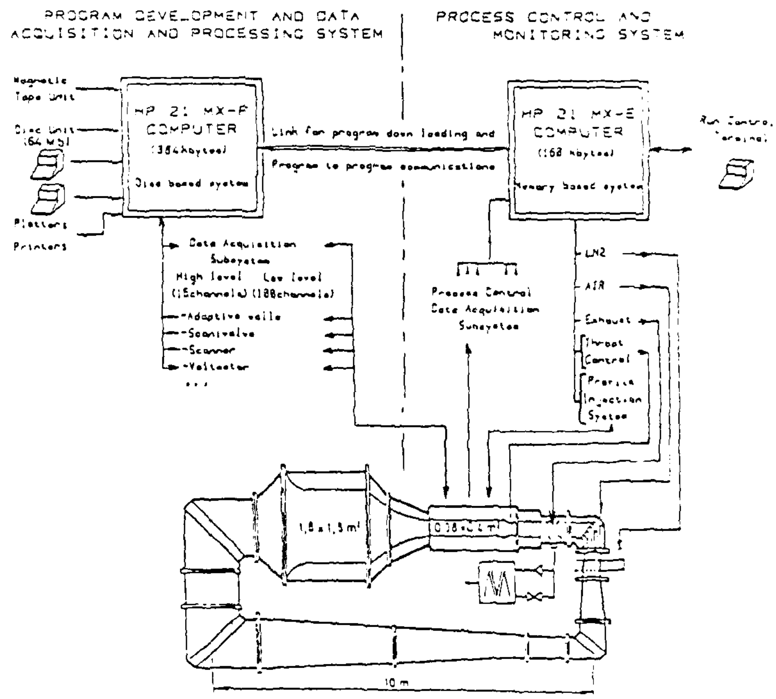


Fig. 6 - T2 facility

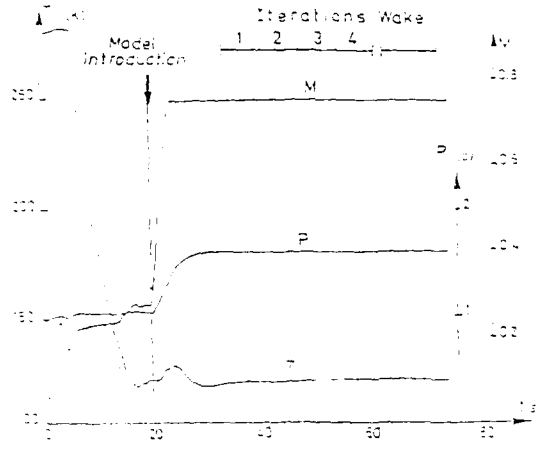


Fig. 7 - T2 typical cryogenic run with adaptive walls and airfoil precooling

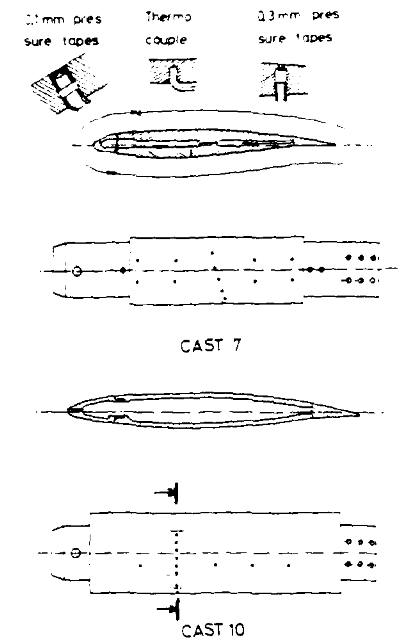


Fig. 8 - CAST 7 and CAST 10 cryogenic airfoil models

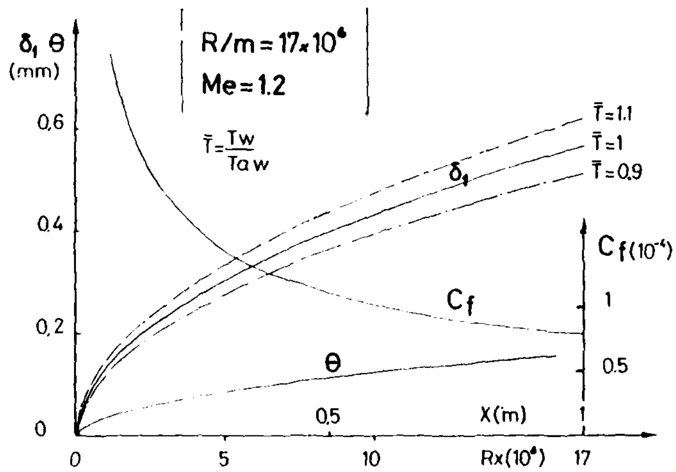


Fig. 9 - Laminar boundary layer development on a flat plate at M = 1,2 $R_e/m = 17.10^6$

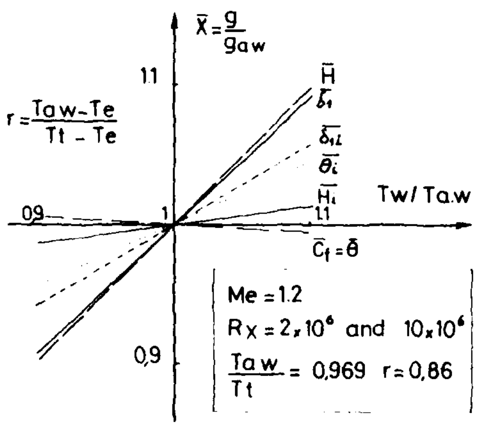


Fig. 10 :- Wall temperature effect on a laminar boundary layer at M = 1,2, R_x = 2 and 10 millions

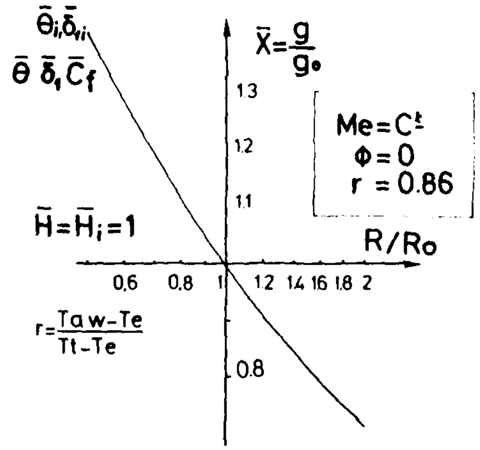
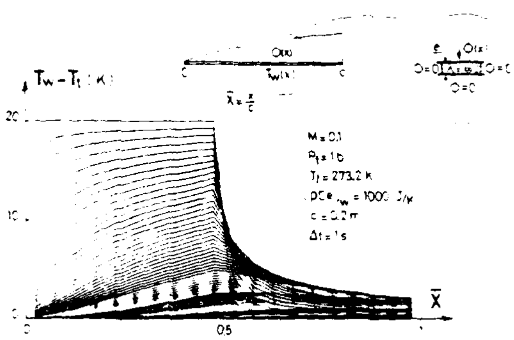


Fig. 11 - Reynolds number effects on a laminar boundary layer at a constant Mach number, Ø = 0.



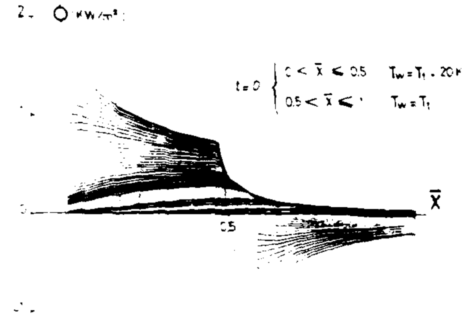


Fig. 12 - Calculated temperatures and fluxes transient for a laminar boundary layer on a thin flat plate without longitudinal conductivity.

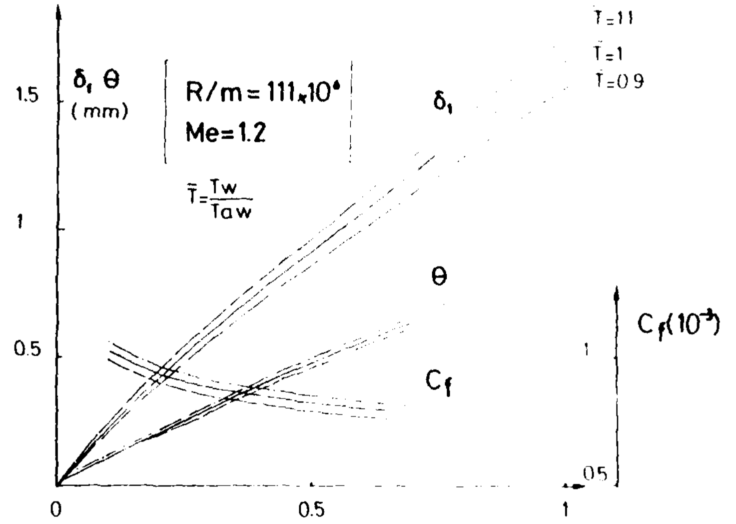


Fig. 13 - Turbulent boundary layer development on a flat plate at M = 1.2

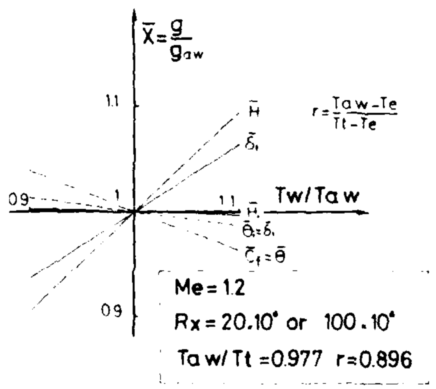


Fig. 14 - Wall temperature effect on a turbulent boundary layer at M = 1,2, R_x = 20 and 100 millions

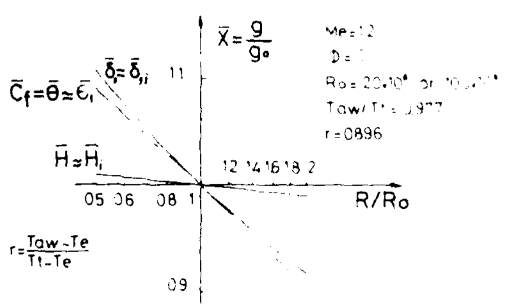


Fig. 15 - Reynolds number effects on a turbulent boundary layer at M = 1,2, R_x = 20 and 100 millions

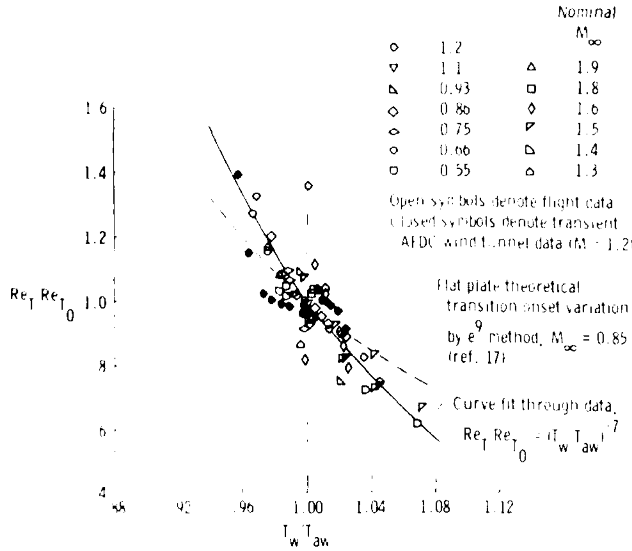


Fig. 16 - Effect of wall cooling and heating on Reynolds number Re_T and comparison with theoretical and experimental results.

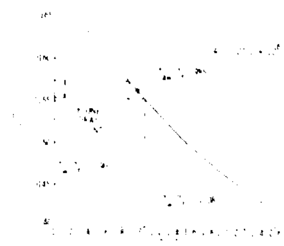
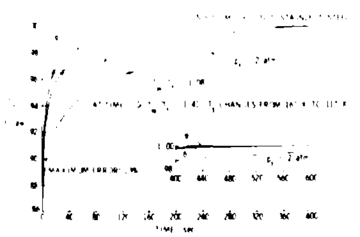
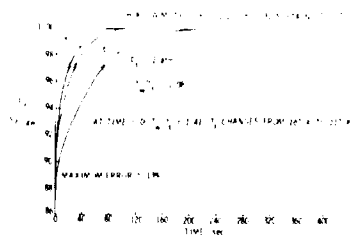


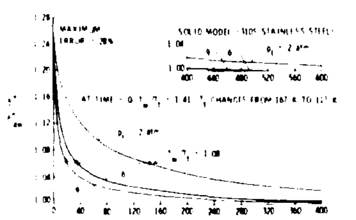
Fig. 17 - Section drag coefficient of NACA 12-64 airfoil as a function of T_w/T_t ratio (M = 0,85, P_t = 2 bars, T_t = 116 K, C = 25,4 cm) from C.B. JOHNSON (Nasa Langley).



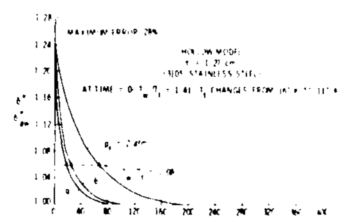
Departure of local skin friction from the adiabatic wall value as a function of time for the NASA body of revolution (M_∞ = 0.85, x/ℓ = 0.5, ℓ = 121.92 cm).



Departure of local skin friction from the adiabatic wall value as a function of time for the NASA body of revolution (M_∞ = 0.85, x/ℓ = 0.5, ℓ = 121.92 cm).

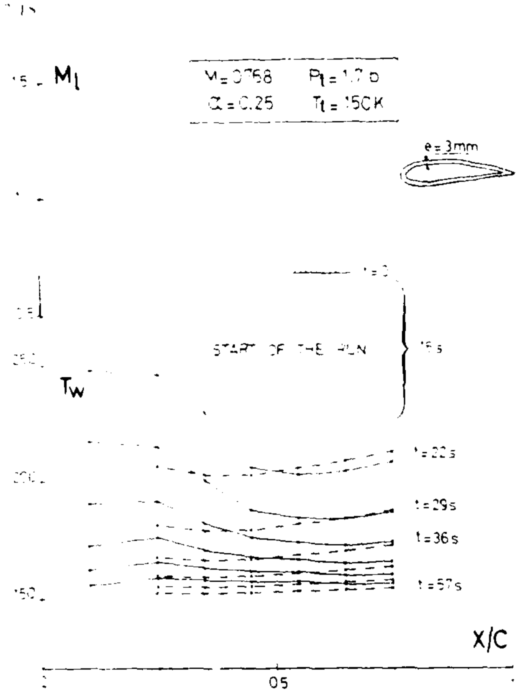


Departure of displacement thickness from the adiabatic wall value as a function of time for the NASA body of revolution (M_∞ = 0.85, x/ℓ = 0.5, ℓ = 121.92 cm).



Departure of displacement thickness from the adiabatic wall value as a function of time for the NASA body of revolution (M_∞ = 0.85, x/ℓ = 0.5, ℓ = 121.92 cm).

Fig. 18 : Exemples of boundary layers stabilisation time after a step from 167 to 117 K for two bodies of revolution solid or hallow from C.B. JOHNSON.



New ideas developed to reduce the thermal inertia at T2 : model cooling by the wind tunnel flow.

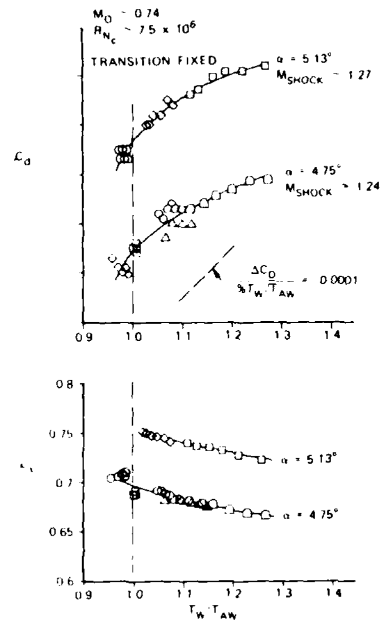
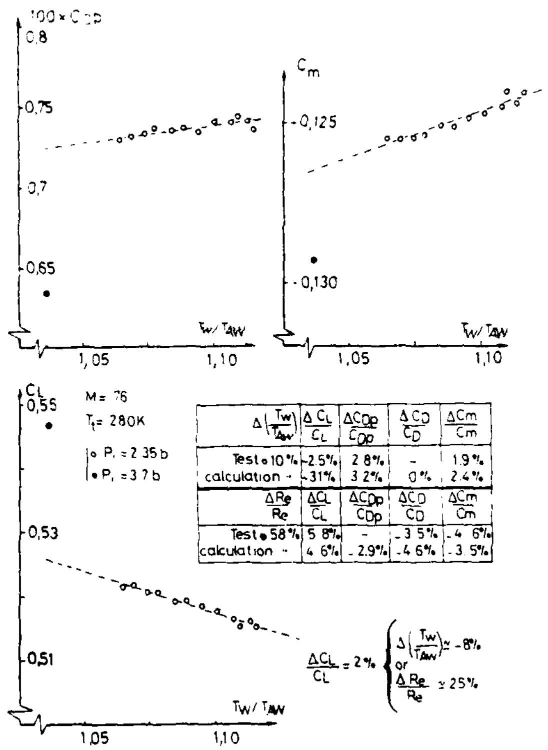


Fig. ... Wind tunnel measured effect of non adiabatic wall on airfoil cruise drag and lift characteristics from F.T. LYNCH and al.

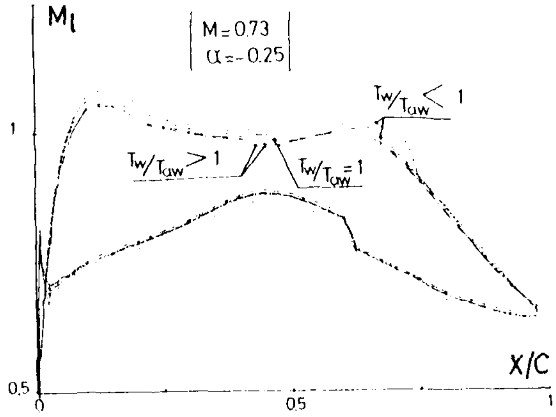


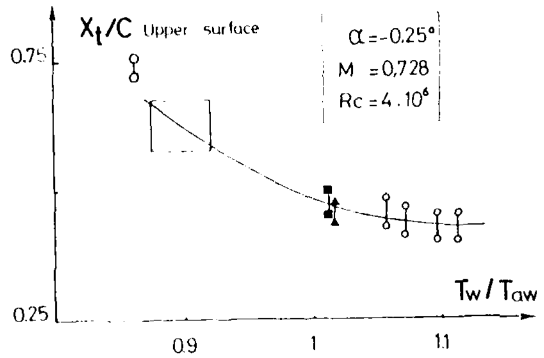
$\Delta\left(\frac{T_W}{T_{AW}}\right)$	$\frac{\Delta C_L}{C_L}$	$\frac{\Delta C_{Dp}}{C_{Dp}}$	$\frac{\Delta C_D}{C_D}$	$\frac{\Delta C_m}{C_m}$
Test ∘ 10 %	-2.5%	2.8%	-	1.9%
calculation -	-3.1%	3.2%	0 %	2.4%
$\frac{\Delta Re}{Re}$	$\frac{\Delta C_L}{C_L}$	$\frac{\Delta C_{Dp}}{C_{Dp}}$	$\frac{\Delta C_D}{C_D}$	$\frac{\Delta C_m}{C_m}$
Test • 58 %	5.8%	-	-3.5%	-4.6%
calculation -	4.6%	-2.9%	-4.6%	-3.5%

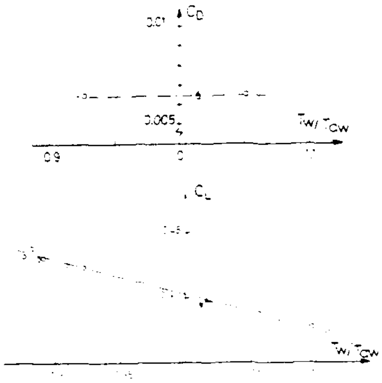
Fig. 21 : T2 wind tunnel measured effects of non adiabatic wall on a CAST 7 airfoil : fixed transition, M = 0,76, α = 0, $T_{ambient}$

Fig. . . - T. wind tunnel measured effects of non adiabatic wall on CAST 10 airfoil with a free transition : M . c) as function of T_w T_{Aw} : M . 0,73, . -0,25, P_t . 1,7 b.

Fig. . . - T. wind tunnel measured effects of non adiabatic wall on CAST 10 airfoil with a free transition : transition location, C_L and C_d as function of T_w T_{Aw}.







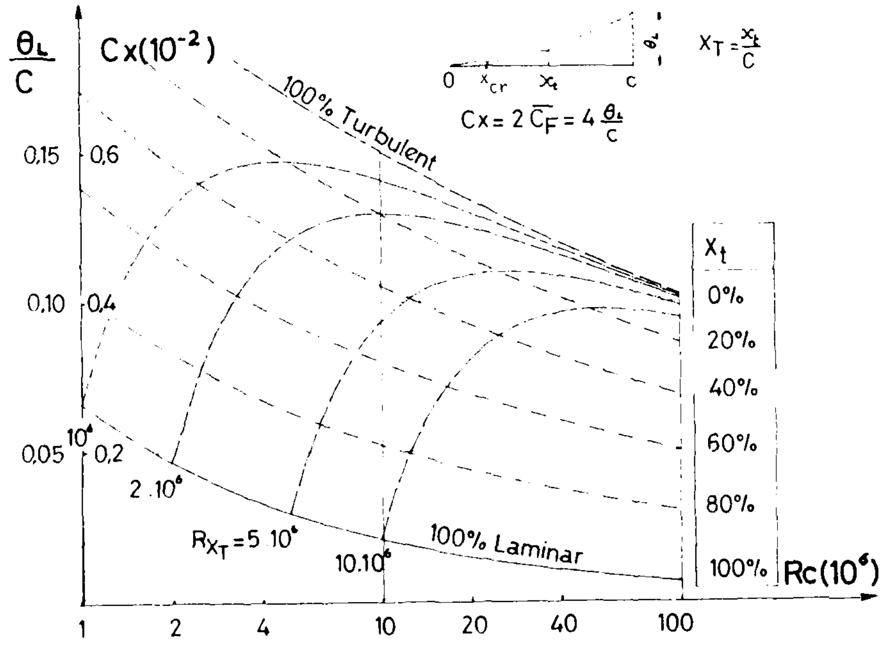
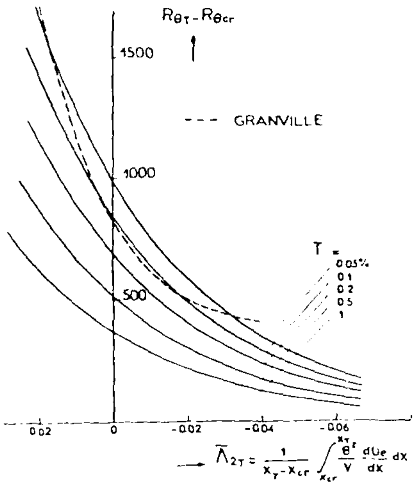


Fig. 24 - Transition phenomena, Reynolds number effects on a flat plate with a free and fixed transition at low Mach number in a simple approach



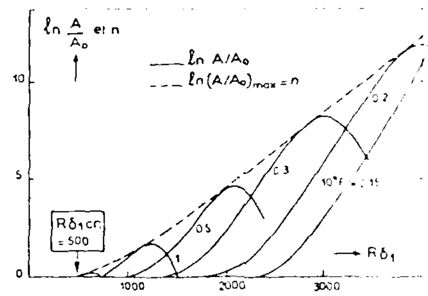


Fig. 25 - Two dimensional transition : criterion developed at the ONERA

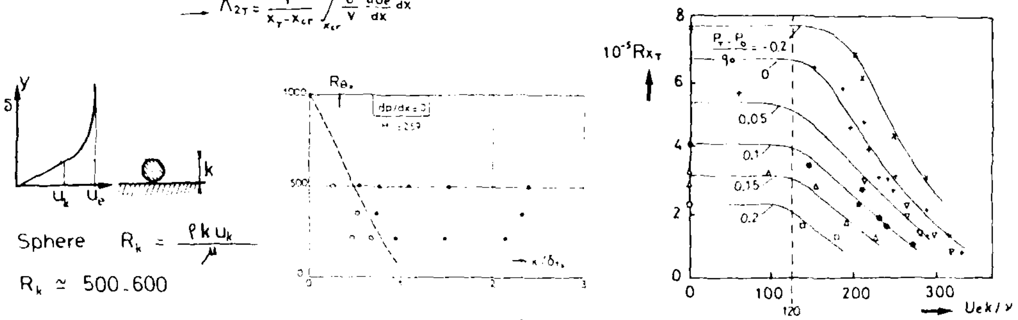
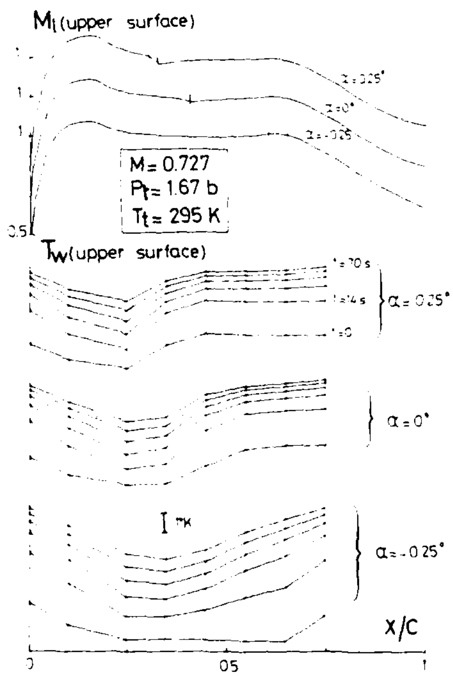


Fig. 26 - Influence of wall roughness : 3 D, 2 D, distributed



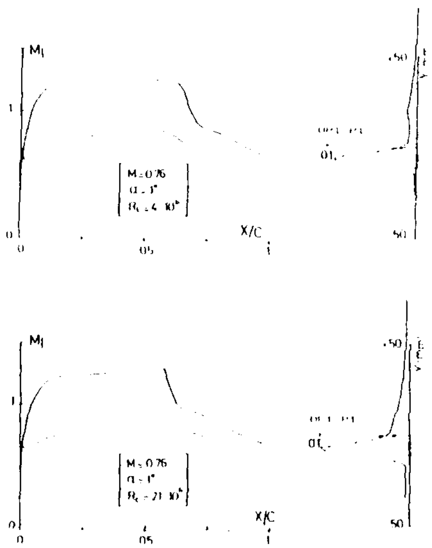


Fig. 28 - Wake measurements : comparison between a laminar and a turbulent interaction (shock wave, boundary layer).

Fig. 27 - Experimental technique developed at T2 to qualify the transition location : $T_w(x,t)$ and $M(x/c)$.

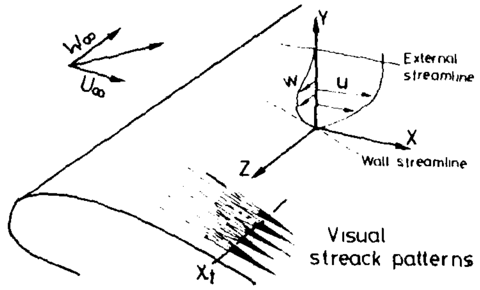


Fig. 29 - Three dimensional transition phenomenon : transverse profile instability

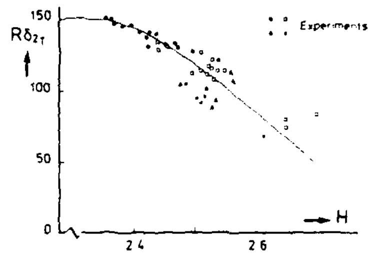


Fig. 30 - Three dimensional transition : criterion developed at the DERAT

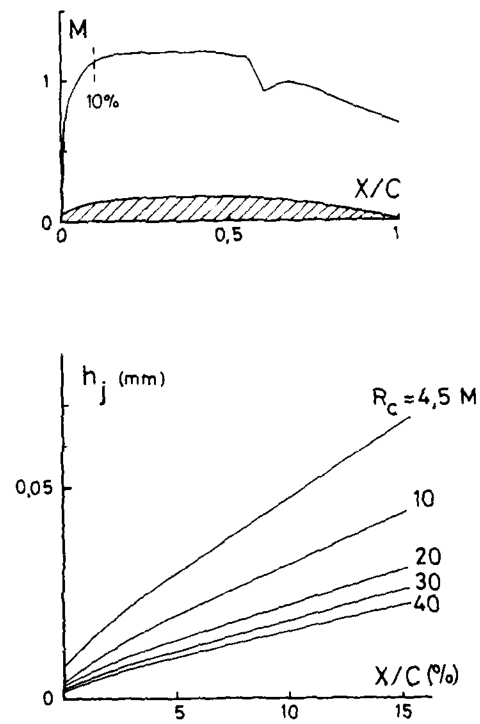


Fig. 31 - Two dimensional boundary layer tripping : effect of R_e, R_{XT} and of the carborundum height for a typical transonic case

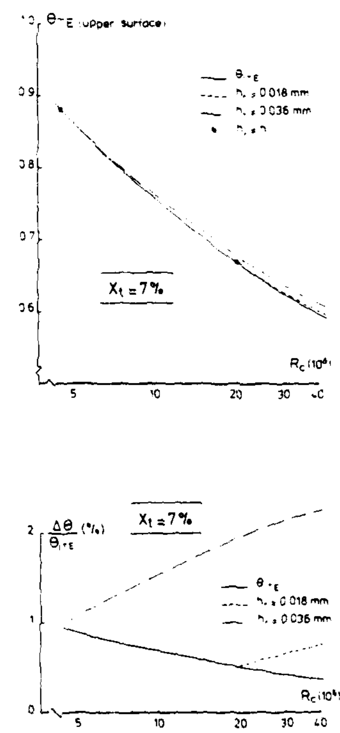


Fig. 32 - Two dimensional boundary layer tripping : problems due to an over thickness of the boundary layer as a function of the Reynolds number.

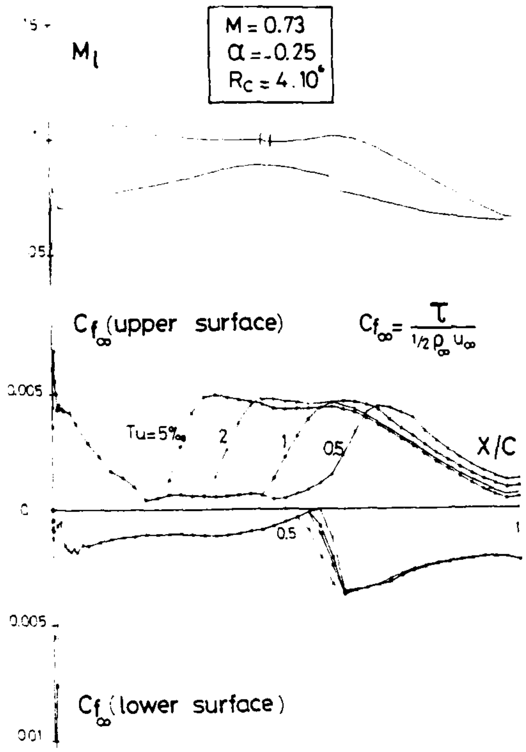


Fig. 33 - Transition location control : visualization, bump on the Mach number distribution and calculation with different Tu

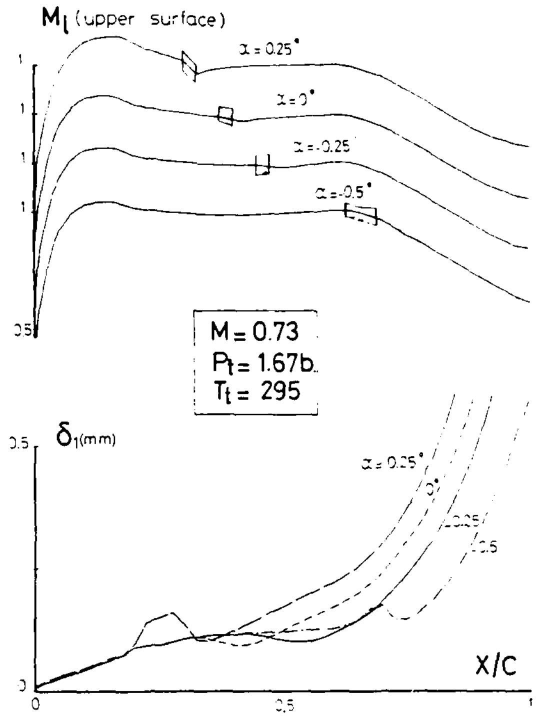
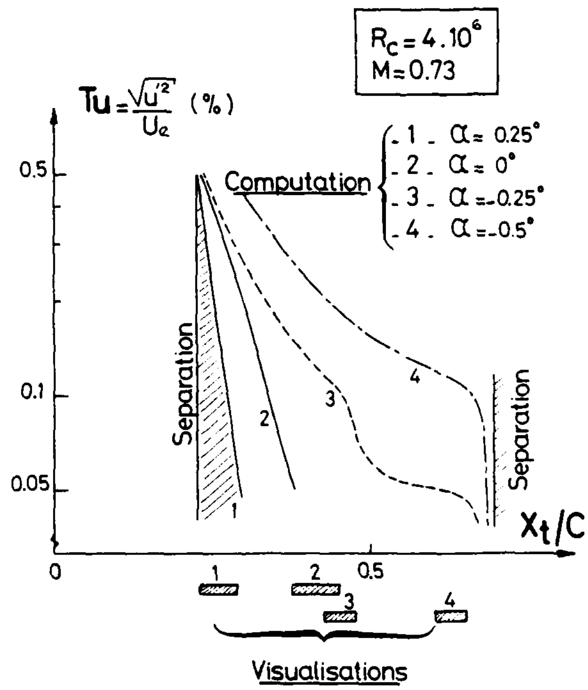


Fig. 34 - Explanation of the Mach number bump by the variation of the displacement thickness δ_1

Fig. 35 - Correlation on transition location (experiments, calculations) for different angles of attack



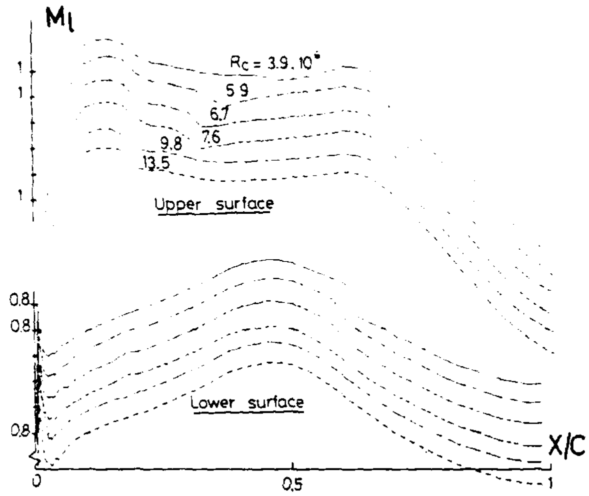


Fig. 36 - Reynolds number effects on transition location at M = 0,73 and α = - 0,25° : M(x/c) as function of R_c

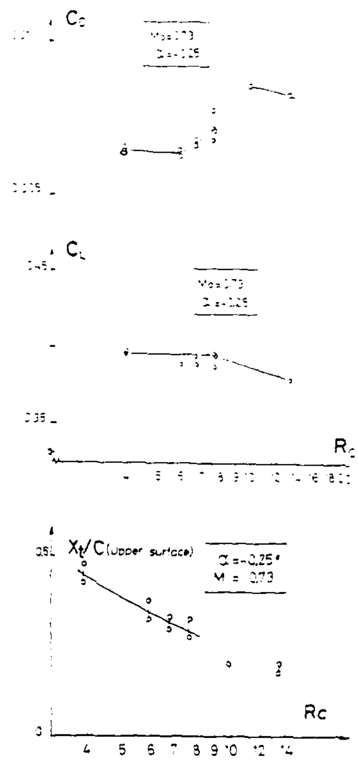


Fig. 37 - Reynolds number effect on the transition location at M = 0,73 and α = -0,25° : X_T, C_L and C_D as function of R_c.

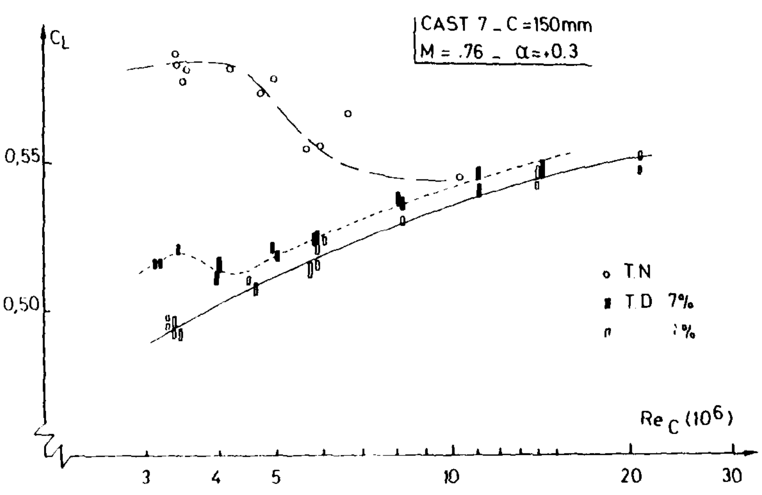


Fig. 38 - Reynolds number effect on the lift coefficient for the CAST 7 (c = 150 mm) tests : fixed transition at x/c = 3 and 7 %, M = 0.76, α = 0.3°

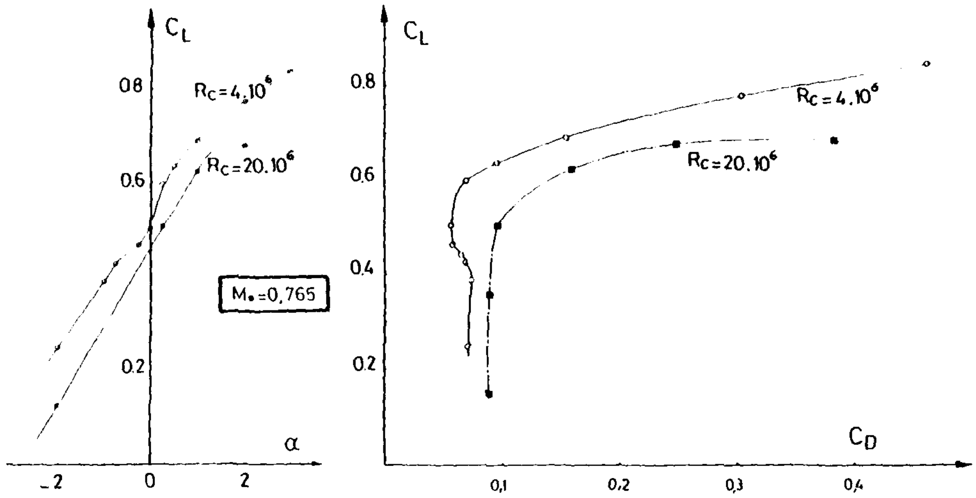


Fig. 39 - Typical free transition results obtained at T2 with the CAST 10 airfoil : $C_L(\alpha)$ and $C_L(C_d)$ at M = 0.765.

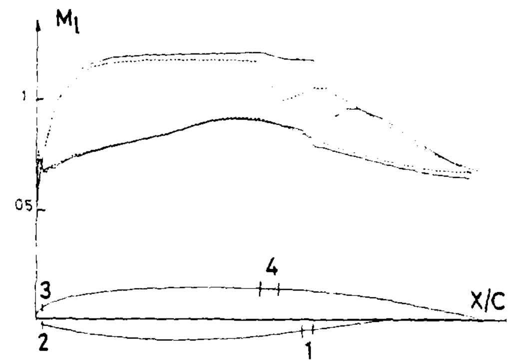
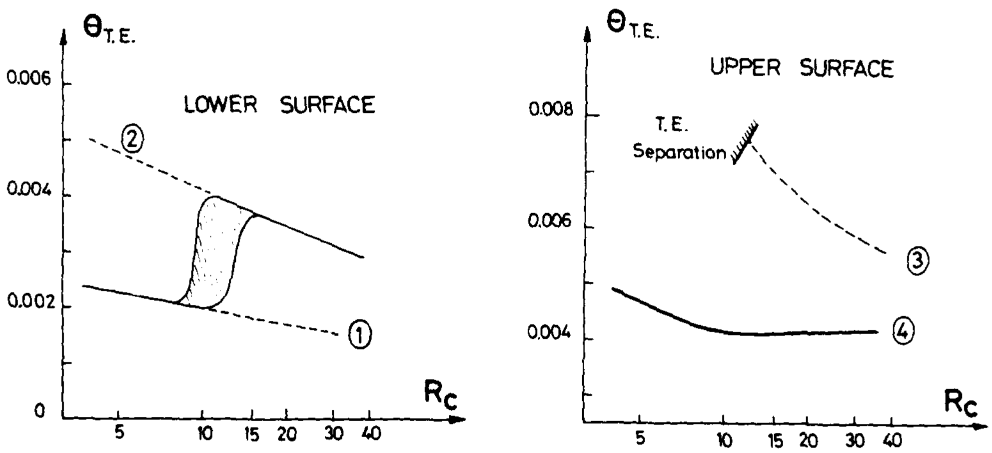


Fig. 40 - Reynolds number complex effects : calculated variations of T.E. as function of the Reynolds number.



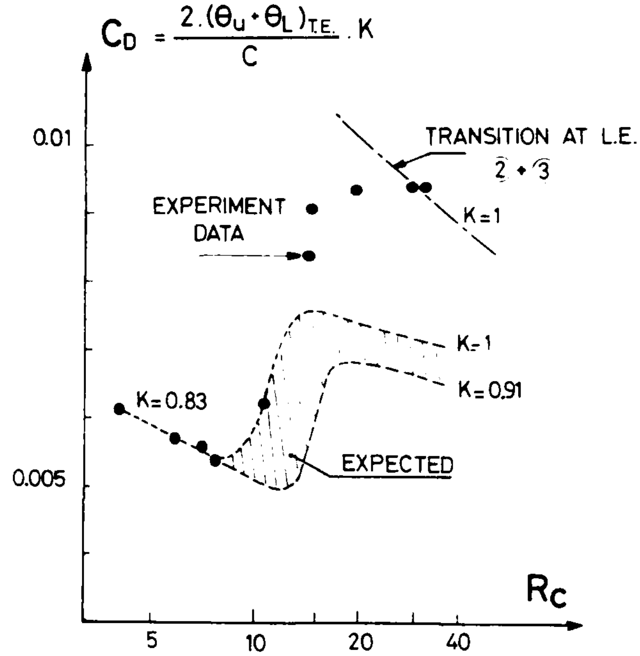


Fig. 41 - Comparison between the measured drag and a theoretical approach

NEEDS IN INSTRUMENTATION

- MODEL ATTITUDE (FLEXIBILITY)
- MODEL ROUGHNESS CONTROL
- BALANCES
- SURFACE MEASUREMENTS
  - . TEMPERATURE DISTRIBUTION
  - . WALL STREAMLINE VISUALIZATION TECHNIQUE ?
  - . WALL HEAT FLUXES
  - . WALL SKIN FRICTION
  - . LOCALIZATION OF THE BOUNDARY LAYER TRANSITION
- GENERAL FLOW CONFIGURATION AROUND THE MODEL
  - . OPTIC SYSTEM
  - . PROBING SYSTEM
- PROBES : P_t , T_t , P, ...
- PRESSURE TRANSDUCERS : CRYOGENIC, SCANNING SYSTEM

Fig. 42 - Needs in instrumentation

PRODUCTIVITY: THE ECONOMIC ASPECTS OF CRYOGENIC WIND TUNNEL DESIGN AND USE.

by J. Christophe

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ABSTRACT

After briefly reviewing the idea of productivity, we examine how it is applied to large non-cryogenic wind tunnels. These considerations can be extended to the new cryogenic wind tunnels; but these have some special features we attempt to define precisely. We then examine the more important focal points in designing a cryogenic wind tunnel for good productivity in operation.

1 - INTRODUCTION

The first steps in applying cryogenics to wind tunnel design and construction demanded much thought and experimental verification concerning the validity of the principle, the way of applying it and the means to be used. Ideas of productivity were left aside for the time being. However, in going from the small experimental systems to large wind tunnels, the designer and future user must search for productivity the same way they have for many years now with the large non-cryogenic wind tunnels.

However, cryogenics wind tunnels have specific features. The fluid used, very cold nitrogen, is a medium hostile to man. Thus, the idea of gaining access to the models and wind tunnel itself, already difficult when going from nonpressurized to pressurized wind tunnels, is further complicated by the temperature parameter. Liquid nitrogen is a relatively expensive product that must be economized. For this reason, the cryogenic wind tunnel operates in "blowdown" mode even if the wind tunnel is designed to operate continuously, with a fan.

2 - THE IDEA OF PRODUCTIVITY AND ITS APPLICATION TO WIND TUNNELS

The term productivity first designated the capacity to produce, or the state of being productive.

This idea has been studied for several centuries in economics, which we can define as the "human science of obtaining wealth" and is thus related to the idea of efficiency. However, the word itself did not take on its current meaning until quite recently [1]. *It can be defined as the quotient of total* production divided by one of the factors of production, *e.g.* the productivity of labor is the quotient of production divided by the time worked:

$$\text{Productivity} = \frac{\text{Production}}{\text{Hours worked}}$$

More generally, productivity is the quotient of the product divided by the added value of all of the factors used.

The quality of the production, and thus the service rendered, should also be taken into acount.

Applied to scientific research, *this idea of productivity brings up the difficulty of quantifying* both the numerator (quantity and quality of scientific production) and the denominator (the money expenditures attached to a certain action), plus the hours of work devoted to it. It may even lead to a total rejection of this mercantile idea by the researcher, who will attach importance only to the quality of the result, without considering the denominator.

It is nevertheless absolutely necessary that this idea be applied to research installations that employ a large work force and expend large quantities of energy.

For a large wind tunnel, used both for research and technical assistance to the aerospace industry, it is clear that the numerator can be evaluated as a certain number of tests, and as the production of data *in the form of a certain quantity of acquired measurements*, curves, tapes and test reports that are finally applied to the construction of a high-performance aircraft. Therefore, the greatest number of tests must be performed, providing the highest quality data, on a yearly basis, for instance. The denominator, on the other hand, can be expressed as a cost, including the total energy *used in running* the test, the hours of work paid to personnel for preparing, running and analyzing the test, computer expenses and general costs: purchases, maintenances, overhead and amortization.

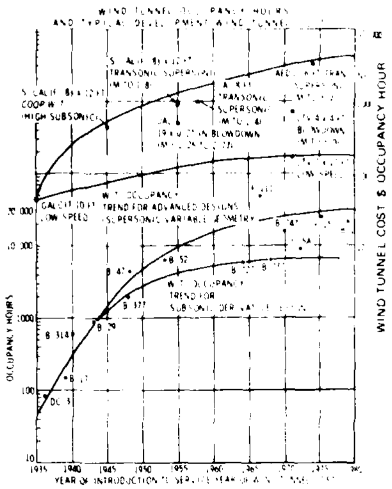


Fig. 1 - Time Growth of wind tunnel occupancy hours used in aircraft development, and wind tunnel costs.

	$ MEGAWATT-HOUR	1000 MEGAWATT-HOURS USED
AMES	18.4	195.5
LANGLEY	30.4	137.9
JOHNSON	37.9	146.4
LEWIS	39.9	161.2
MARSHALL	41.4	96.5
GODDARD	45.2	91.5
MICHOUD	47.5	79.3
KENNEDY	48.0	181.6
DOWNEY	59.1	102.2
JPL	59.7	67.6
AEDC	61.0	

Fig. 2 - Energy rates and total energy used for various facilities in FY 1981.

Fig. 1 shows the historic increase in the number of wind tunnel occupancy hours needed to develop an aircraft, and the cost of the wind tunnels expressed in hours of occupancy [2]. Expenditures for wind tunnel tests are only a small part of the cost of a major project. The authors of [3] indicate that a $30 to 40 million wind tunnel test expenditure, including the price of the models, for an airliner program is only 2% of the total program cost.

Although this percentage is small, it is still a large sum and, in each test center, there is a constant effort to reduce costs [3 and 4]. However, comparing test costs between different organizations in different countries is difficult because of the different ways the occupancy time is evaluated, e.g., whether or not the amortization is to be introduced and because of the large differences in the cost of energy.

Figure 2, taken from [3], shows the variations in the cost of energy for different test centers in the United States.

Figure 3, which is also taken from [3], shows the cost per hour of occupancy and the percent of power cost in the total cost, for several wind tunnels.

TUNNEL	TYPE	SIZE	BASIC COST*	POWER	TOTAL COST	POWER COST / TOTAL COST
			Dollars per occupancy hour			
Ames	Transonic Atmospheric	14'	1 450	400	1 850	21,6%
Ames Unitary	Transonic Pressure	11' X 11'	1 750	850	2 600	32,6%
Boeing	Transonic Atmospheric	8' X 12'	2 355	160	2 515	6,4%
Calspan	Transonic Pressure	8' X 8'	2 260	340	2 600	13%
Ames	Low Speed Pressure	12'	1 000	400	1 400	28,5%
Boeing	Low Speed Atmospheric	5' X 8'	475	10	485	2,1%
Convair	Low Speed Atmospheric	8' X 12'	550	80	630	12,6%
Rockwell	Low Speed Atmospheric	7-3/4' X 11'	550	80	630	12,7%
University of Washington	Low Speed Atmospheric	8' X 12'	235	20	255	7,8%
Vertol	Low Speed Atmospheric	20' X 20'	1 600	200	1 800	11,1%

* Includes labor, maintenance, depreciation, computing, etc.

Fig. 3 - Typical Transport Aircraft Testing costs (1981 Base). These costs are estimated from past Boeing experience and actual bill.

For the installations considered, this ratio goes from 2.1% for a small subsonic wind tunnel, and at atmospheric pressure, to 32.6% for a large pressurized transonic wind tunnel.

Through the remainder of this paper, productivity will not be expressed by a total number, but rather we will only examine the way each term in this quotient should be influenced. Money values will be used with the greatest caution, and time or energy units and dimensionless expressions will be used when possible in their stead.

3 - RESEARCH PRODUCTIVITY IN CONVENTIONAL WIND TUNNELS

Improving the quality of the tests, to meet the ever-increasing requirements of industrial research groups requesting the tests, is a continuous job calling for patience and consistency. One example is ONERA's Modane-Avrieux center, where this effort has been going on for 30 years now [5].

This quality term, difficult to quantity but quite real, must be associated with a quantity term: the reduction of wind tunnel occupancy time for a given test or, in other words, an increased number of tests in a given time. Associating the two terms increases the product, which is the numerator in the productivity quotient.

It is interesting to see how wind tunnel occupancy time is broken down. Fig. 4 shows this in three pie charts. The first is for the S2MA wind tunnel at the Modane center, and is averaged over the three-year period 1981-1983. The 25% test run share became 30% in 1984. The other two pie charts (unpublished) given by Boeing in 1980 are for the Boeing transonic wind tunnel in Seattle and the 12-foot NASA ARC wind tunnel at Ames [6], respectively.

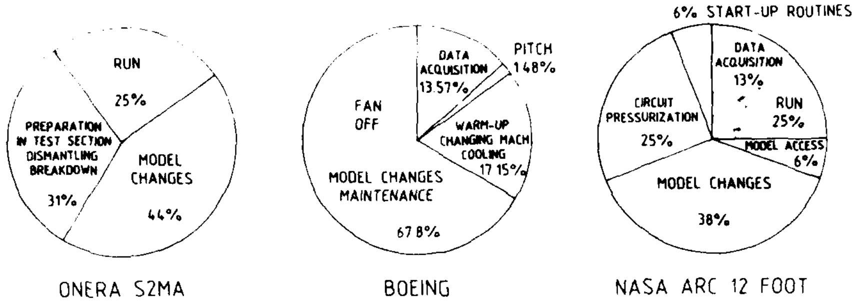


Fig. 4 - Occupancy time distribution.

This occupancy time is subdivided into two main parts:

- the 68 to 75% of the total time with the fan off, for test section preparation, model installation, disassemblies and configuration changes

- the 25 to 32% running time, half of which goes to establishing the test conditions, such as the Mach number, and the other half of which goes to data acquisition.

Reducing the length of each test program, to carry out the greatest number of tests in a year, entails:

- reducing the running time by automating the test sequence (wind tunnel, model supports and model controls), real-time monitoring of the essential test parameters, reliability of the measurement systems and the use of high performance computers

- but also reducing the fan off time, which will be examined in greater detail at the end of section 3.

Then, looking at the denominator of the productivity expression, it is quite clear that lowering the rotation time reduces the energy expended, and reducing the occupancy time lowers the number of personnel hours; but this latter point must be considered in a larger context.

3.1 - *The test: Overall operation*

The efficiency goal is not limited to the test execution phase. It must be applied to the entire period going from the test definition down to the production of data because, during this period, a rate is applied to personnel hours to establish the cost of the test.

This whole operation includes:

a) Engineering design:

- model definition

- definition of test setup and supports

- verification of the aerodynamic validity of the setup, and of the model and test setup strength

- definition of the model instrumentation and equipment.

b) Construction, instrumentation and checking of the model and test setup

c) Operational test of the entire assembly, outside the test section before the test. It is desirable that this verification, which should cover all of the test setup and model equipment, be carried out under conditions as close as possible to wind tunnel conditions.

d) Wind tunnel tests.

Equipment and method reliability must first be established before undertaking this phase of the whole operation, as defects appearing during the tests cause test delays and upset the wind tunnel program for the following test.

The ways of reducing the wind tunnel test time were spoken of above, in the analysis of the occupancy time.

e) Results.

One of the reasons for using high performance computer systems is to fully understand the test while the test is going on, by generating near-real time data. This way, the test can be controlled interactively.

The final goal is to shorten as much as possible the time needed to generate the full set of test data once the test is finished.

If each of these operations is made more efficient, the total number of hours devoted to the the whole test program is reduced.

Finally, in searching for greater productivity, the importance of efficient personnel must not be forgotten. As J.F. Wendt expressed it so well in a recent report, "A requirement which is often overlooked is trained personnel—both engineers and technicians. **Productive wind tunnels** are those in which a team of people have been working together for at least a few years and which are supported by an instrumentation branch. **Experience in running** facilities, in selecting appropriate measurement techniques compatible with data needs, tunnel characteristics and data handling systems; and **in the development** of new measurement techniques **cannot be purchased;** it must be developed and systematically utilized".

This remark, which applied here to wind tunnel operation, also applies to its design.

5.2 - Reducing the time off. Importance of the "test section area."

The long intervals, mentioned above, during which a wind tunnel is occupied with the fan off are due to the model installation, adjustment and disassembly, and to configuration changes carried out on the model during tests. Carrying out all of these operations outside the test sections, then instantly replacing one model with the other, would be an ideal case in which the occupancy time without rotation would be zero. This is impossible to attain.

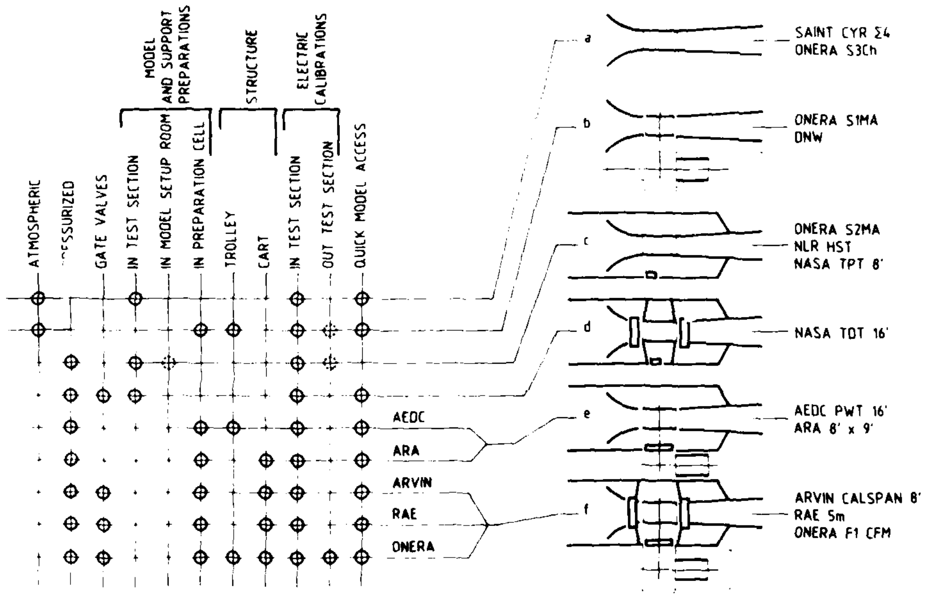


Fig. 5 - Organization of the "test section area".

Fig. 5 compares the "test section area" organization for different wind tunnels, of the type:

- without trolley or cart: nonpressurized (*a*) or pressurized (*c* and *d*). The model setup/disassembly and configuration changes can only be made inside the test section. However, to save time, the model, balance and sting can be prepared outside the test section and then placed inside. This is the method used at the S2MA.
- with a moving element carrying the model. The test setup is assembled and disassembled outside the wind tunnel. For *b*, and *e* (AEDC), a trolley carrying the model is used, where the trolley ensures the circuit continuity. By using several trolleys (three at the S1MA), tests can be prepared simultaneously.

For *e* (ARA) and *f*, the model is carried on a cart. At the ARA, a moving trolley at the diffuser entrance frees the end of the test section so that the cart carrying the model can be removed. This cart is normally placed at the end of the test section. At the Calspan and RAE, the cart also serves as the

lower part of the test section. It is rotated some 90° and then moves out through a side door. At the [illegible] tunnel, the cart, which is also the floor of the test section, is carried out on a trolley, and is taken off the trolley to be moved into the assembly area. These wind tunnels all have several carts, making it possible to prepare several tests simultaneously.

At the F1, each cart has its own acquisition system. This means that the test can be fully simulated (except for the wind) in the assembly cell, including the connection to the main wind tunnel computer. Gates are provided in configurations [illegible] and [illegible] so that the "test section area" can be depressurized without depressurizing the rest of the circuit. The [illegible] 16-foot wind tunnel uses freon in certain cases, and the gates are absolutely necessary to keep from losing the gas. Considering the size of the compressor and compressed air storage facilities, the type [illegible] wind tunnels would be completely useless without these gates, because of the emptying and filling ti[illegible] that would be needed each time the configuration is changed, regardless of how simple it is. The volume of the F1 is 13,000 m^3, which corresponds to a [illegible] variation in the mass of the air between 1 and 4 bar. The volume between the gates is only 500 m^3.

This description shows how important it is that the test section area arrangement be thought out at length. One or more tests must be prepared outside the test section, acting on a single element, while one test is going on inside. The model, its balance and supports and a "piece" of the test section itself must be treated as a single element, whatever type setup is used. It is of great importance for the simplicity and efficiency of the final design that the "piece" of test section be chosen prudently. In effect, once the reliability and speed of the test section entrance/exit is known, we can determine the time when the model has to be taken out of the section for modification. The time needed gets shorter as the speed and reliability increase.

Particular attention should be paid to the electrical (and fluid) connections, which must be entirely automated, whether the acquisition system is part of the cart or is fixed.

Experience shows that, even in a continuous wind tunnel like the F1, the high speed of the acquisition systems may cut test times between configuration changes down to just a few minutes. The desire for productivity should stimulate an attentive study of how to motorize the models and to optimize the test program sequence.

4 - THE CRYOGENIC WIND TUNNELS

The above considerations on how to increase the productivity of conventional wind tunnels also apply to cryogenic wind tunnels: but the new stagnation temperature parameter T_t, which varies from 300 K to 100 K, and the cost of liquid nitrogen introduce special new conditions:

- With the cost of liquid nitrogen, some way is sought to reduce the fan rotation time during which, in steady regime, the added liquid nitrogen essentially offsets the energy added by the fan and, for a small part, the thermal losses. To do this, the automatic systems adjusting p_t, T_t and M and the automation of the model support ought to undergo particular study. These short rotation times bring out the transient character of conventional wind tunnel operation, where starts and stops are frequent, as opposed to industrial systems that operate almost continually.

- These transient states vary the temperature of the wind tunnel elements, which affects the consumption of liquid nitrogen. Special attention should be paid to the temperature conditioning of the wind tunnel.

- Using a medium hostile to man means that there is no simple way of gaining direct access to the model or to the other wind tunnel elements. Special attention must be paid to the accessibility and handling conditions and the temperature conditioning of the model. Although less frequent and justified only for checking and maintenance purposes, access to the other elements cannot be neglected either.

- The accessibility conditions must be such that no water, carbon dioxide or dust enter the tunnel itself.

4.1 - *Important points to be considered*

A wind tunnel client's first question is, "What will the test program cost?" To run the greatest number of tests at the lowest cost, an exhaustive list must be made of the points to be considered during the cryogenic wind tunnel design.

To do this, it is convenient to consider the table of contents of the specification for a typical project. This can be seen in Fig. 6, where the table of contents contains *nine chapters*. The typeface for the various chapters indicates the importance assigned to those subjects during the wind tunnel design phase, when analyzing the future productivity of the system. These are:

- the test spectrum retained, which determines the number of technological alternatives and provides an answer to another of the clients questions, "What tests are possible, and how much versatility do I have?" The test spectrum idea is defined in section 4.3

- the thermal insulation mode, which largely determines the versatility of the test execution, the wind tunnel temperature conditioning and the operating cost

- the test section access conditions

- the model handling conditions

- the model temperature conditioning.

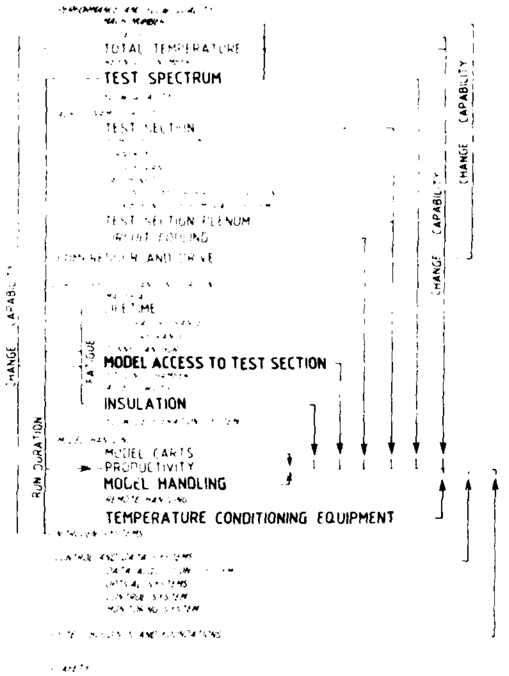


Fig. 6 - The main topics.

It should not be concluded from this list that, for example, chapter 7, on the control and data systems, is of no importance. On the contrary, it is essential to wind tunnel productivity. In particular, the performance of the servo system for, the stagnation pressure *pi* or *po*, the stagnation temperature *Ti* or *To* and the Mach number *M* must be studied more carefully. However, even if the means involved are complex, at least they are not unknown.

On the other hand, the points just listed are strongly interactive, and there is a definite lack of experience in dealing with them.

Fig. 6 also attempts to show the different elements contributing to wind tunnel productivity, and the interaction between these and other important items such as structural fatigue, rotation time, versatility of test conditions.

4.2 - Operating Cost

NASA engineers have estimated the cost of nitrogen expended during NTF rotations [7, 8, 9]. Fig. 7 summarizes the performance of the NTF and indicates the expense in dollars per second while the wind tunnel is running steady state, during which the nitrogen flow compensates the power the fan dissipates into the circuit.

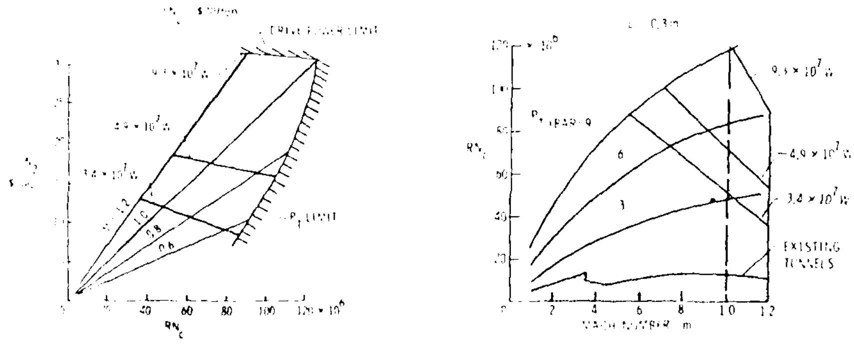


Fig. 7 - Plot of LN_2 cost rate versus Reynolds number for the NTF, showing different levels of the Mach number and drive power. Plot of maximum Reynolds number versus Mach number for the NTF, showing levels of power required.

The maximum expenditure goes up to $30 per second. The authors estimate that, for a Boeing 747 model tested at the actual flight Reynolds number, the expense would be $10 per second, or $6000 for an ten-minute rotation.

The cost of using the ETW for a year was estimated on the basis of 5,000 polars per year, broken down into 500 rotations for 15 test programs in 42 weeks (Fig. 8). This cost was calculated adding $A + B + C$, where A is the cost in energy (on-site liquid nitrogen plant), B is personnel costs and C is the cost of maintenance, insurance and other costs, but not including amortization. With an initial energy cost assumption, the cost was broken down $A = 50\%$, $B = 31\%$ and $C = 19\%$. Taking the most optimistic price for electrical power and the installation of the liquid nitrogen plant, A can be reduced to 35%.

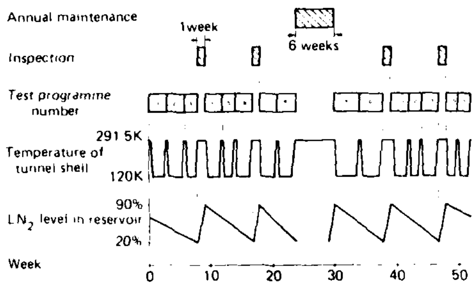


Fig. 8 - Assumed annual operating schedule.

From these two calculations, it seems that:

- the energy cost is a large part of the budget. Fig. 3 indicated 2.1 to 32.6% for the power cost, out of the total cost. The same calculation for the large wind tunnels at ONERA gives 7 to 15%, depending on the wind tunnel. It should nonetheless be noted that, in these two cases, the amortization is counted in, which reduces the share of the power cost.

- the high instantaneous mass flow of nitrogen flow will encourage experimenters to reduce the running time by all possible means, in particular by high performance automation. It is still desirable to increase the number of tests each year, but the ratio of rotation time to occupancy time is less significant as an efficiency factor. The fan wind tunnel tends to become a long-blowdown tunnel.

Energy Consumption

Using the assumptions of the ETW technical group, the annual consumption of liquid nitrogen is evaluated at 70,000 metric tonnes, subdivided as follows:

- Consumption for 500 rotations (considering that a single polar graph of force measurements requires 15 sec, and 60 sec for pressure measurements) 29 000 t

- 500 repressurizations and fan starts 7,000 t

- conditionings 32,000 t

- miscellaneous 2,000 t.

The conditionings include liquid nitrogen expenditures from heat losses, drainings and cooling operations for certain wind tunnel elements. In particular, the share of conditioning in the total cost includes 15 coolings of the entire circuit from 291.5 to 120 K, each requiring 620 t, and 20 cart coolings from 291.5 to 120 K, consuming 30 t per cooling.

Under the same conditions, the fan power consumption is 3400 MWh. The Technical Group equates 1 t of liquid nitrogen with 0.9 MWh. The 70,000 t thus corresponds to 63,000 MWh of electrical power consumed by the nitrogen plant. The share of the fan is almost marginal.

Remarks on the energy characteristics of liquid nitrogen and on the different types of wind tunnel

The cooling capacity of liquid nitrogen as a function of the temperature is given in figure 9. At a pressure of one bar, the nitrogen will have absorbed 434 kJ/kg going from the liquid state to the gaseous state at 300 K. At 120 K, the figure is 245 kJ/kg, and 200 kJ/kg to go to 77 K (latent heat of the vaporization).

The *L'Air Liquide* company estimates that 0.72 kWh are needed to manufacture 1 kg of liquid nitrogen, or 26,000 kJ/kg. 1 kg of gaseous nitrogen at 300 K from the plant circuit costs 860 kJ, while it would cost 3,034 kJ to derive it from liquid nitrogen.

These figures merit attention. As George Claude pointed out, "Thus what is remarkable in liquid air is not at all the "quantity" of cold involved, but the "quality" of this cold, *i.e.* the extraordinarily low temperature it makes possible. However, by its very quality, this cold, stored in the liquid air, is obtained at high cost" [10, p. 211].

These energy characteristics, and the large share of the nitrogen in the total cost of use, incite us to compare the consumption of nitrogen for various types of wind tunnel. In the Agard lecture series no. 111 of May, 1980, R. Michel presented the variation of the mass flow rate of liquid nitrogen with respect to the mass flow rate in the wind tunnel test section, as a function of the stagnation temperature in *blowdown*, *induction-driven* and *fan-driven* wind tunnels (Fig. 10) [11].

For the direct blowdown wind tunnel, we can simply say that the flow through the test section Q_v is equal to the sum of the blowdown air or nitrogen flow Q_R plus the injected flow of liquid nitrogen Q_{N_2}, and that the fluid Q_R should be brought to its temperature of origin T_R to Ti. To do this, it must be cooled by the liquid nitrogen flow Q_{N_2}.

This produces the relation:

$$\frac{Q_{N2}}{Q_v} = \frac{1}{1 + \frac{B}{T_R - T_i}} \text{ , where } C_p = 1 \ \frac{kJ}{kg \cdot K},$$

in which B is the ordinate in figure 9, for each value of Ti.

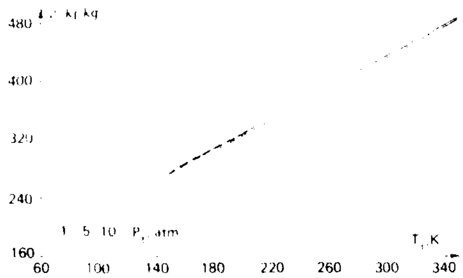


Fig. 9 - Specific cooling capacity of nitrogen as a function of tunnel stagnation temperature for various values of tunnel stagnation pressure.

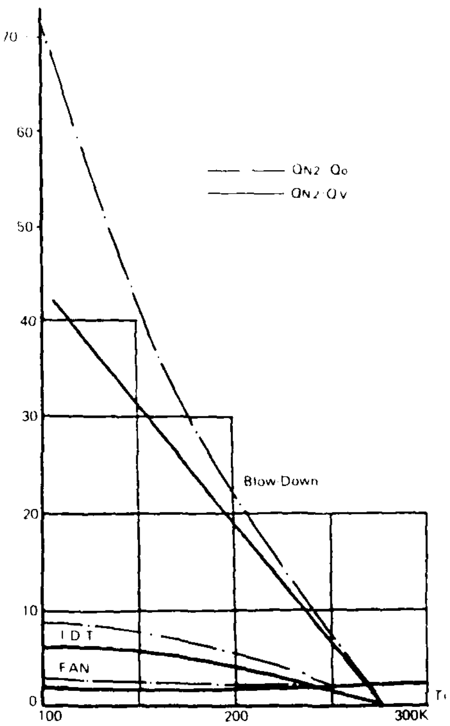


Fig. 10 - Liquid nitrogen consumption of various wind tunnels.

This type of tunnel inspired a series of very interesting studies by J.D. Caldwell, J.F.L. Aldrich and M.L. Fincher of the *Douglas* company; however, the *Douglas* four-foot CWT wind tunnel is now abandoned. *It seems that this type of direct blowdown tunnel is justified only for small sections.*

It is of interest to make a deeper comparison between the type T2 injection wind tunnel and the NTF or ETW type of fan wind tunnel. The consumption is plotted in figure 10, assuming a wind tunnel load loss $\Delta pi/pi = 10\%$. For this fuller comparison, the rates of flow are taken with respect to the flow Qo in the test section at temperature T_R, instead of Qv. Keeping the Mach number and stagnation pressure the same, $Qv = Qo \sqrt{TR/Ti}$. This way of representing the flows shows the absolute value variation of the variable better, as it is taken with respect to a constant (Ref. Fig. 10). The fan power is taken with respect to Qo. Fig. 11 shows the variaton of W/Qo and Q_{N_2}/Qo for various values of the temperature Ti and the fan compression ratio $\bar{\omega}$.

The characteristics of the T2 wind tunnel were used to represent the induction-driven tunnel. These are: drive flow Mach number $Mi = 1.6$, driven flow Mach number in the straight section before the injector $M_1 = 0.6$, ratio of the mixing section to the injection section $\lambda = 20$. The flow rates Q_{N_2}/Qo and Q_G/Qo, where Q_G is the injected gas flow rate (air or nitrogen), that depend on Ti and $\bar{\omega}$ (Fig. 12).

Considering the curves corresponding to $\bar{\omega} = 1.09$ for the induction-driven wind tunnel (T2, at $M = 0.9$) and $\bar{\omega} = 1.14$ for the fan wind tunnel (NTF, at $M = 0.9$), it appears that:

- the rate of liquid nitrogen flow is nearly independent of the temperature for the fan tunnel. The

induction-driven wind tunnel requires less flow at high temperature, but some three times more at low temperature, than the fan tunnel.

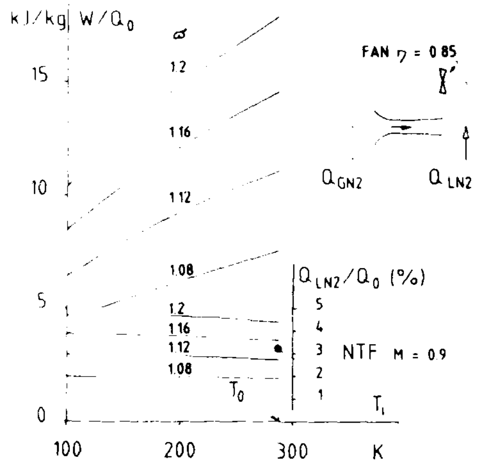


Fig. 11 - Fan power and liquid nitrogen consumption for a wind tunnel driven by fan.

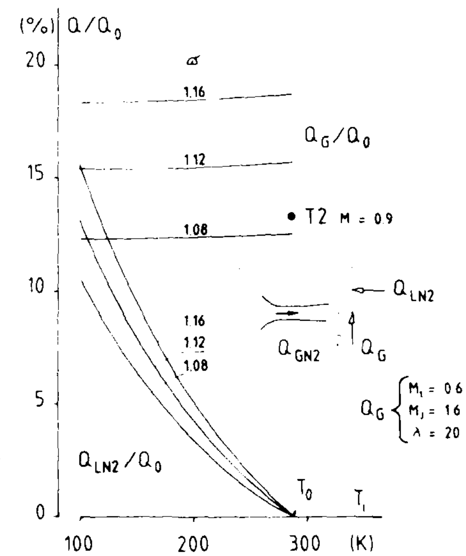


Fig. 12 - Nitrogen consumption for an air driven wind tunnel.

- if the induction-driven tunnel use pure nitrogen, some six times more nitrogen is needed than in the fan tunnel; but the injected gas is practically independent of the temperature.

The above considerations apply once the wind tunnel is operating in steady state. In fact, to make a good comparison, we would have to use the annual consumption, which is the product of an instantaneous rate of consumption over an interval of operation. These intervals are not necessarily the same for one or another alternative. They depend on the test spectrum and on the proportion between the useful operating time, when measurements are being taken, and the operating time wasted on test condition changes. In this respect, the induction-driven wind tunnel is certainly more versatile than the fan tunnel. It is also important to consider the consumption of nitrogen in the transient states, *i.e.* when the test conditions are changed, as these are affected by the thermal insulation conditions. The induction-driven wind tunnel with nearly total insulation and short blowdowns minimizes the losses. The following sections will attempt to answer these questions.

Remarks on the cost of energy

However, before closing this section, a few thoughts on the cost of energy seem to be in order.

Each year, the *Union International des Producteurs d'Electricité* ("UNIPEDE") draws up a comparison of electric power costs in various countries. Industrial consumers are classed in families by type (*A*, *B*, *C1*, *C2*, etc.), defined by the power of the installation and the annual consumption. Fig. 13 shows this domain of industrial uses of electricity, plotting the figures for ONERA's F1, S1 and S2 wind tunnels, the ETW nitrogen plant (LN2) and the ETW fan.

For the hydraulic turbine-driven S1 and S2 tunnels the power consumption was converted into equivalent megawatt-hours.

Though the nitrogen plant corresponds to industrial-type consumption the wind tunnels are characterized by their high power but relatively low power consumption due to their transient operation.

Fig. 14 compares the costs of electrical power (VAT not included) on January 1, 1984, for the *UNIPEDE* families. The jags in the curves are due to the differences between the fixed and proportional parts, which depend on the family. The cost figures given are for an ETW contract in France including the fan + site base load + LN2, the fan + site base load, and for the "over-the-fence" nitrogen production plant located next to the wind tunnel.

It should be noted that these costs are based on official non-negotiated *Electricité de France* prices. The vertical lines indicate the range of possible contracts, depending on the client's constraints (peak hours, withdrawal, etc.). For the nitrogen plant, only the optimal alternative is indicated.

These costs confirm that the wind tunnel is not a typical consumer but nitrogen production is the dominant element in the total cost and could be supplied at a much lower rate.

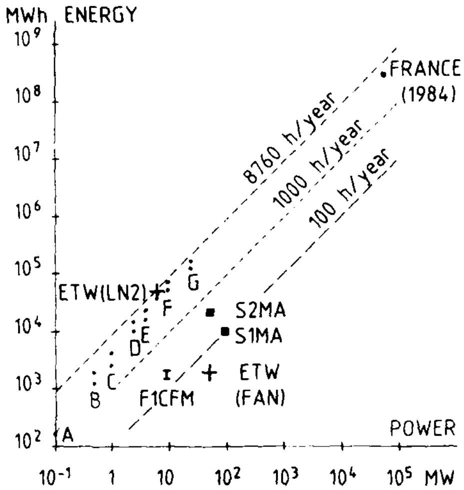


Fig. 13 - Industrial supply of electricity and specific aspect of wind tunnel supply.

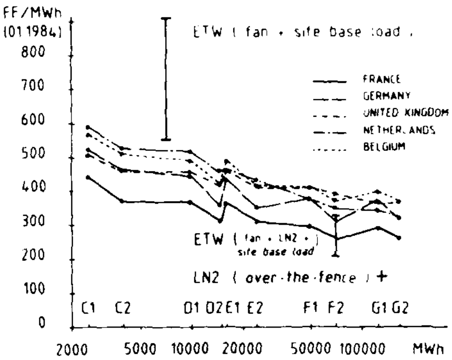


Fig. 14 - Electric energy cost comparison.

On this point, by examining the cost of liquid nitrogen under various conditions of sale, it can be shown how seriously this point needs to be discussed. At the end of 1984, the retail price (VAT not included) for liquid nitrogen in France was 2300 F/t in 600-liter units, while it was 1440 F/t in 300-liter units and 1140 F/t for the CERT T2 tunnel. We saw above that the 1980 price for the NTF supply was announced $70 per ton (1 ton = 0.972 tonne), which currently corresponds to a price of a 750 F/t.

Nitrogen delivered by truck in West Germany is apparently bought at 150 DM/t, or 458 F/t.

In France, the cost of nitrogen, without counting the amortization, would be 211 F/t for a nitrogen plant that is part of the wind tunnel, and 178 F/t for an over-the-fence supply from a private manufacturer. These prices assume that 100% of the nominal production is consumed. At 50%, the costs are 287 F/t and 226 F/t, respectively, and at 25% they are 452 F/t and 330 F/t.

4.3 - *Test spectrum*

We mentioned above that the test spectrum is an essential element in wind tunnel design and versatility, and must also be known if we want to determine the cost of operation, as the cost is strongly affected by the configuration changes and the resulting transient consumption of liquid nitrogen. However, the term *test spectrum* is not yet clearly defined, and can in fact be given several definitions.

Firstly, we can attempt to break down the (M, R) field into areas, and assign operating times to these different areas based on users' statements concerning the frequency of tests at low or high Mach numbers and high or low Reynolds number. Fig. 15 shows one breakdown of this type from the ETW study phase, in its first 1.65 m · 1.95 m version. This figure is given only as an example and the reader is asked not to attach any absolute value to the percentages but simply to observe the clear trend when the high percentage of cold tests is high.

It is rather difficult to extract any definite information from figure 15, where the two parameters *pi* and *Ti* operate simultaneously. The way the wind tunnel performance is presented in figure 16 makes it easier to see the effect of the three parameters M, *pi* and *Ti* simultaneously on the variations of the dynamic presssure q and on the Reynolds number. The limit at the left of figure 16 is the saturation at a point in the flow where M = 1.7. However, the ETW project is designed for $Ti \geq 90$ K.

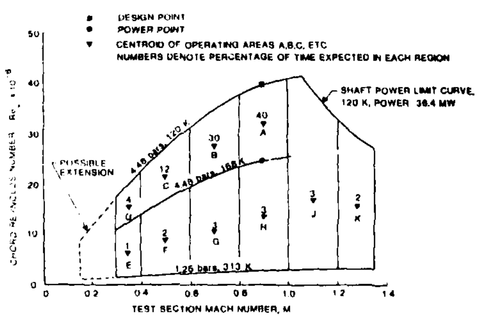


Fig. 15 - Operating envelope with test time distribution.

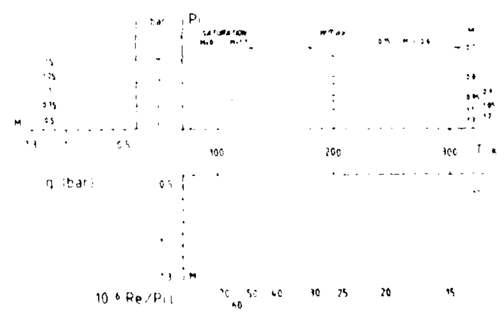


Fig. 16 - Operating envelope showing pi, Ti, M, q and R_e/Pi.l.

The test time probability distributions for the ETW have been plotted as a function of three parameters *M, pi* and *Ti*, based on a survey of future ETW users [12 and 13]. The users were asked to project the tests needed for the next 15 years taking into account the practical constraints concerning the model (temperature equilibrium and deformations), the wind tunnel (thermal fatigue of the structure) and also the power consumption and occupancy time. The survey data show the following percentage breakdown of the test time as a function of the temperature conditions:

- atmospheric temperature (> 270 K) 6.5%
- constant low temperature (< 150 K) 70%
- constant intermediate temperature 14.5%
- temperature variation during one rotation 9%.

Fig. 17 shows the stagnation temperature and stagnation pressure distributions and figure 18 shows the Mach number distribution in greater detail.

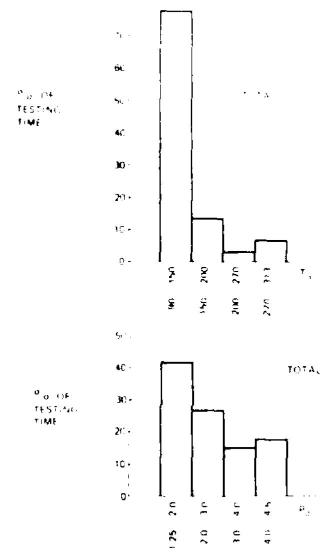


Fig. 17 - E.T.W., pressure distribution and E.T.W., temperature distribution.

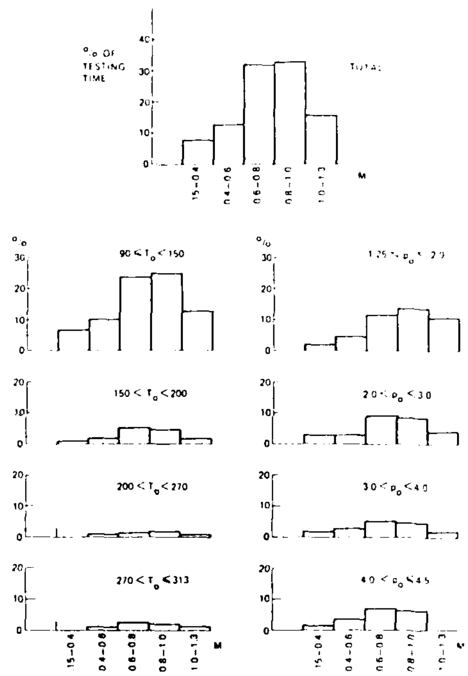


Fig. 18 - E.T.W., detailed Mach number distribution.

These histrograms show a large demand in the 0.6 < M < 1.00 domain, especially in the low temperatures and moderate pressures (some 40% from 1.25 to 2 bar and 25% from 2 to 3 bar).

However, in addition to these overall observations (Figs. 8, 15, 17 and 18), a closer and more realistic look must be taken at the typical test programs (boxes numbered 1, 2, 3, etc., in figure 8) and the sequence during each rotation in the program. This constitutes a real test spectrum. Figures 19 and 20 give a picture of one run at a constant temperature and another with the temperature varying.

All of these transient states, as well as the pre-sequence and post-sequence coolings and warmings, and the warmings and coolings between rotations, must be compatible with the strength of the structure. They also affect the consumption of nitrogen.

Much more than for a conventional wind tunnel, the optimal program analysis is needed in the operational phase and is indispensable in the design phase, to make sure the expected installation capacities are compatible with the users' demands.

A civilian aircraft program producing 2000 polar graphs, including 1600 force measurements and 400 pressure measurements, comprises 16 test programs on a full model and seven with a half-model, or an average of some 85 polar graphs per test program. In each test program, we find some ten Reynolds number changes. There are three to six operations on the model for 100 polar graphs.

A military aircraft program producing 2000 polar graphs includes 27 test programs, each generating 60 to 100 polar graphs, but with 129 interventions on the model, or an average of 15 polar graphs between each intervention and 74 polars per test program.

A military aircraft requires a greater number of interventions, and it seems unlikely that the model can be motorized. It is very important to know if, for a given mechanical configuration, it is desirable to vary the wind tunnel conditions or if frequent assemblies and disassemblies are permissable to adapt the configuration to the wind tunnel state (temperature level).

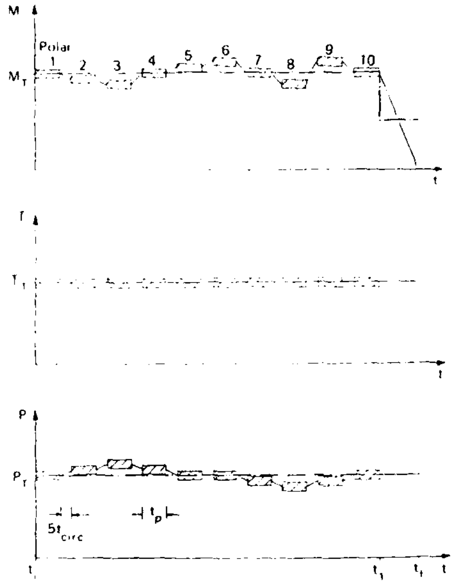


Fig. 19 - Sample of run with constant temperature.

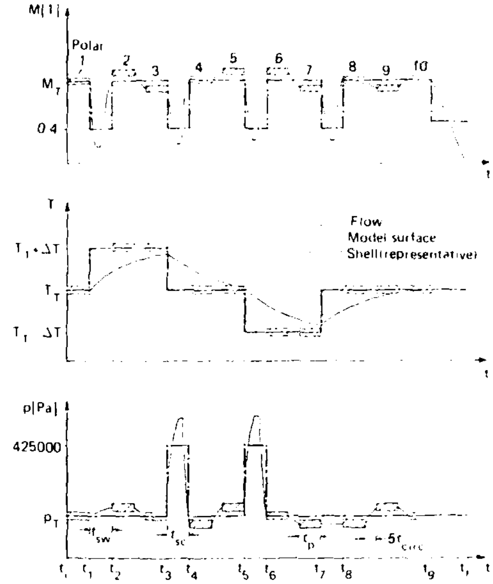


Fig. 20 - Sample of run with temperature changes.

4.4 - *Thermal insulation*

NASA's 0.3 m TCT continuous wind tunnel at Langley uses external insulation. The entire light metal structure undergoes the temperature variations [9 and 14].

The ETW wind tunnel project with its 2 m · 2.4 m test section uses the principle of the coldbox that envelopes the entire circuit, providing external insulation. The entire steel structure undergoes temperature variations [13].

The KKK subsonic wind tunnel with its 2.4 m · 2.4 m test section and concrete structure, has internal insulation [15].

NASA's NTF wind tunnel at Langley, with a 2.5 m · 2.5 m test section, is insulated internally [7, 8, 9, 16 to 23]. The internal insulation, on the structure that withstands the tunnel pressure effects, is thick enough that the effects of the temperature variations on the structure can be neglected. On the other hand, the internal structures are not insulated (Fig. 21).

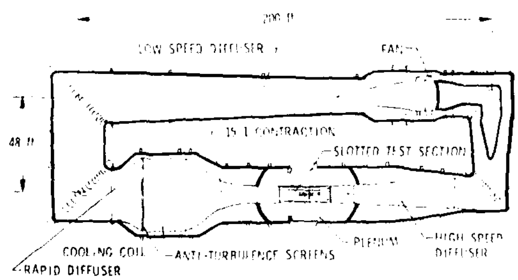


Fig. 21 - National transonic facility insulation.

ONERA's induction-driven T2 wind tunnel, with its 0.4 m · 0.4 m test section, has internal insulation, except for the honeycomb and the screens. All of the internal elements, and the shell that contains the pressure, are insulated [24].

This internal insulation is thus almost total. Although the insulation is thin, a relatively short blowdown time (some 60 sec.) means the structure is practically unaffected by the temperature variations. This design makes for great versatility as concerns pressure and temperature changes.

The research currently conducted at the T2 calls for five to ten cryogenic blowdowns per day.

The liquid nitrogen consumed in stabilized regime, without heat losses (Figs. 11 and 12), can only be reduced by reducing the test time.

The conduction losses through the walls in steady regime are small, as figure 22 shows for the 0.3-m TCT tunnel [14].

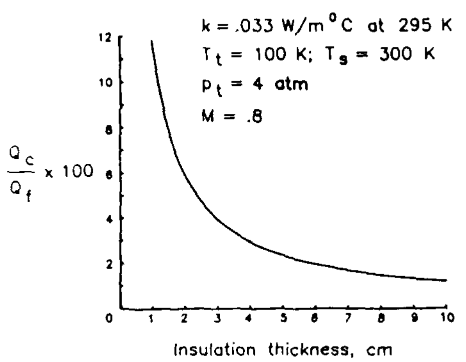


Fig. 22 - Ratio (in percent) of heat input from conduction to heat input from the tunnel drive fan versus insulation thickness.

With an insulator having a conductivity k = 0.033 W/mK and a thickness 0.08 m, the ratio between the energy lost by conductivity and the energy required to compensate the heat added by the fan is only 1.5%.

The largest losses come from the transient states: cooling and heating the uninsulated elements inside the wind tunnel, cooling and warming the structural envelope of the tunnel, if the insulation is external. These transient states directly affect the structural fatigue, which tend to limit the temperature variation speeds.

In the case of the NTF [22], to avoid excessive stressing of the internal structure, the full cooling cycle is slow. Some five hours are needed for the structure to reach temperature equilibrium. This corresponds to a variation rate of 0.75 K/min [18 and 19].

Figure 23 shows an eight-hour cooling/warming cycle and the temperature variations of the fluid as well as of the internal and external faces of an element inside the tunnel [18].

Figure 24 shows a full cooling, during which the flow temperature is lowered beyond the desired equilibrium point, to reduce the time needed to reach equilibrium. The temperature is then allowed to vary ± 48 K (± 86 F), the maximum step to avoid structural limitations [21]. This 48 K temperature variation seems to require 100 sec, according to [22].

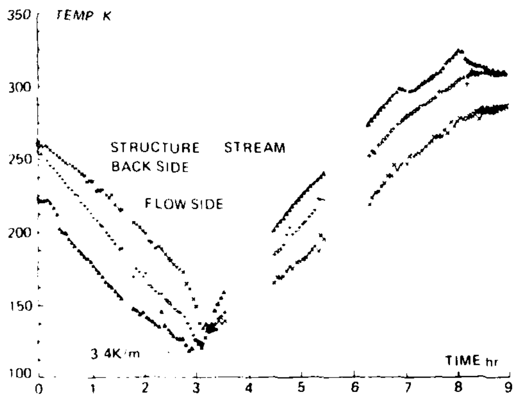


Fig. 23 - Typical operating temperature profile.

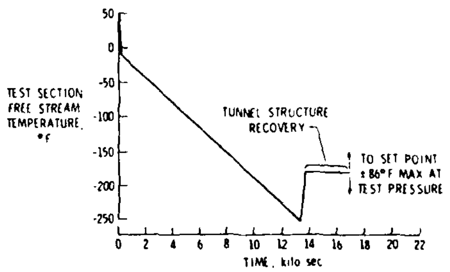


Fig. 24 - NTF model system cooldown - test section conditions.

On the basis of the initial ETW plan and elements already supplied in documents [25, 26 and 27], a few indications will be given on the time constants, the overall behavior in various insulation conditions and the comparison of energies transferred from the fluid to the wind tunnel walls. A new element will be examined concerning the behavior of a stingholder and of a cart.

Time constants

Using the basic principle of the initial ETW design with the 1.65m × 1.95 m test section, we attempted to examine the normal behavior of a wind tunnel, *i.e.*, the temperature variation field of the wind tunnel elements when the fluid temperature varies. These wind tunnel elements can be grouped into three categories: (*i*) those completely immersed in the fluid, such as the honeycomb, meshing and corner vanes, (*ii*) the walls exposed to the flow on one side only, and (*iii*) the other elements that are subjected to the fluid temperature changes indirectly (Fig. 25).

The thermal behavior of these elements as the fluid temperature varies ΔT_F at time $t = 0$ can be expressed as a sum of exponentials:

$$\Delta T_E = \left[\frac{\Delta T_E}{\Delta T_F}\right]_{t=\infty} \cdot \Delta T_F \left[1 - \sum_i a_i e^{-t/CTi}\right],$$ where CTi are the time constants.

If we do not need an exact description of the response at the very beginning of the step, the dominant time constant is sufficient to describe the element temperature variation, which is practically complete (for 95%) at the end of an interval that is equal to *three times this time constant*.

For the conditions p_I = 4.5 bar, T_I = 168 K, M = 0.9, and the known dimensional characteristics of the ETW in its initial version, figure 25 indicates the values for τ and gives a picture of the temperature variations. The wide diversity in the time constants attracts our attention to the precaution to be taken to avoid thermal stresses [27].

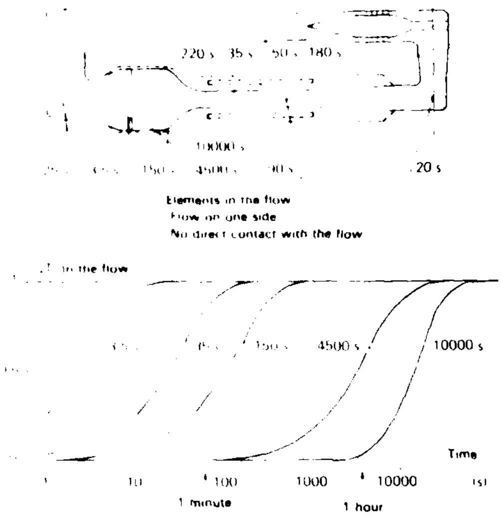


Fig. 25 - Response of the various wind tunnel elements to a temperature step in the flow.

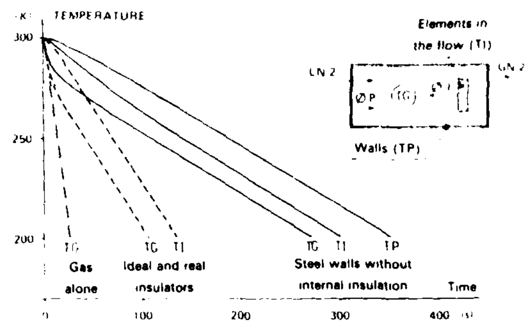


Fig. 26 - Temperature variation of the fluid TG, of the internal elements TI and of the walls TP under the following conditions: liquid nitrogen flow: 50 kg/s: fluid heat capacity: 5 MJ/K: heat storage capacity of the internal element: 21 MJ/K: time constant for these elements: 30s: wall heat storage capacity: 40 MJ/K: time constant of these elements: 80 s.

Overall Behavior

A very much simplified model of the wind tunnel can be constructed to estimate the variations of the temperatures T_g (of the fluid, considered to be uniform), T_I (internal elements) and T_p (walls), with the whole system perfectly insulated from the outside and the fluid mass constant. The conditions for the calculations are indicated in the title of Fig. 26. The curve on the left shows the variation of T_g for a wind tunnel with perfect internal insulation and no internal elements. The two curves in the middle show the variation of the T_g and T_I with a perfect internal insulation, and the last three curves show the variation of T_g, T_I and T_p when there is no internal insulation.

For all practical purposes, the first hypothesis corresponds to the T2 tunnel, in which all of the elements are insulated from the flow except for the settling chamber screen.

In the second hypothesis, corresponding to the NTF, the rate of temperature variation is slowed down because the heat capacity of the elements in the flow is several times higher than that of the gas. We conclude that the heat capacity of the internal elements needs to be reduced, by reducing the mass and by a proper selection of the materials used in constructing them (Fig. 27). A calculation using the characteristics of an actual insulator shows that the temperature changes of the fluid and of the internal elements are practically the same as with a perfect insulator. In fact, the surface temperature of the insulator rapidly reaches a value close to that of the fluid, and the fluxes at the wall are very small with respect to the internal elements.

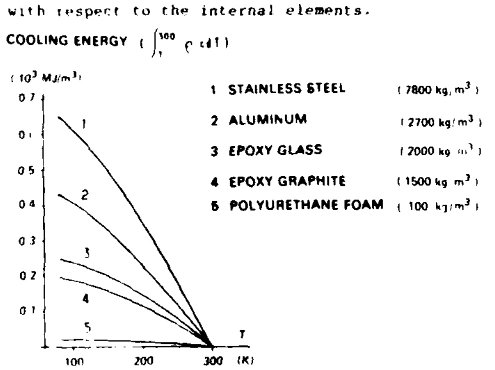


Fig. 27 - Heat storage capacity of various materials.

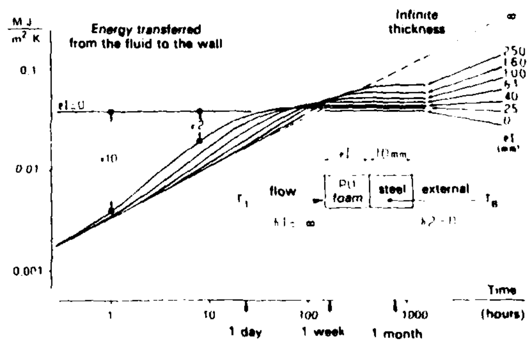


Fig. 28 - Energy transferred from the fluid to the wall when the flow temperature is stepped $\Delta T_1 (h_2=0)$.

In the third hypothesis, the fluid temperature variation is further slowed down because of the energy absorbed by cooling the metal walls of the wind tunnel.

The fluid temperature variation is the same in all three cases at the start of cooling (for a low $\Delta T/\theta$), *i.e.*, before the fluxes appear in the metal wall. When these fluxes become large, the fluid temperature variation slows down.

Transferred Energy

The presence of an insulating wall on the fluid side attenuates the temperature variations of the metal with respect to that of the fluid. This attenuation depends on the thickness of the insulator and also on the tranfer conditions on the metal side. Let us consider an insulated metal wall on the fluid side, to which the fluid applies a high transfer (high h_1), *i.e.*, the insulator surface is roughly at the same temperature T_1 as the fluid (Figs. 28 and 29). We can assume the transfer coefficent h_2 is finite or null on the other face. The first case corresponds to a transfer with the outer medium while the second represents perfect insulation, or a plate with insulation on both sides, for which the flux at midthickness is zero. We will also assume that the temperature T_B is uniform through the plate thickness.

The quantities of energy transferred can be calculated from the transfer functions given in [27].

Figures 28 and 29 show how these quantities vary with time, using values corresponding to an established steady regime, when the fluid temperature is stepped ΔT_1. The energy is expressed in $MJ/m^2{\cdot}K$, *i.e.* for a unit wall surface and a step of 1 K.

For a short time interval, each system of curves is asymptotic with the line of energy transferred for an infinite thickness of insulator (energy proportional to $\sqrt{t}$, thus having a slope 1/2 in logarithmic coordinates). For a long interval, in the case where $h_2 = 0$, the curve tends toward an asymptotic value corresponding to a 1 K reheating of the entire metal wall ($el = 0$), or of the whole metal wall plus the insulating wall. In the case where h_2 is not zero, the asymptote of the curves is the steady state line (energy proportional to t, thus having slope 1 in logarithmic coordinates).

We note that a 250 mm thickness of foam doubles the heat capacity of the 10 mm steel plate. With a 25 mm thickness of foam, the energy transferred in one hour is ten times less than the cooling energy needed to cool the steel. After eight hours, the ratio is two (Fig. 28).

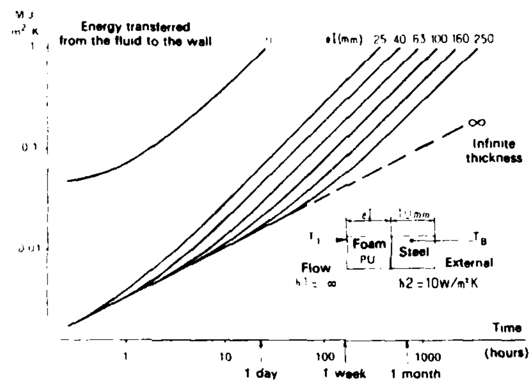


Fig. 29 - Energy transferred from the fluid to the wall when the flow temperature is stepped $\Delta T_1 (h_2)=10W/m^2K$).

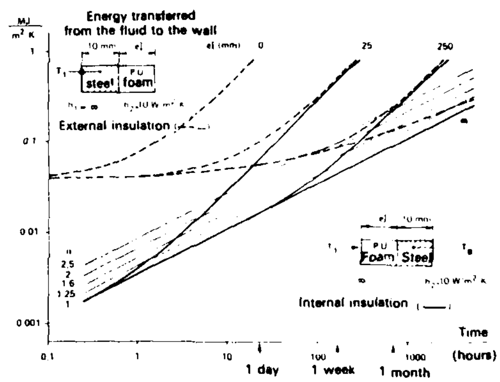


Fig. 30 - Comparison of energy transferred after a temperature step ΔT_1 of the fluid when the sinsulator is internal or external.

Finally, the behavior of a steel wall on the flow side, with insulation outside, can be determined. Using the same hypothesis as above, this wall is instantaneously at the flow temperature. In reality, this is true only after a few minutes. Fig. 30 gives the transferred energy curves and compares them with those of figure 29. For t near zero, the curves tend toward the cooling energy of the metal, and as t tends toward "infinity", they are asymptotic with the curves in the previous case (slope 1). Lines of slope 1/2 are drawn on figure 30 to show n multiples of the minimum energy, which is what is transferred for the case of an insulator of infinite thickness.

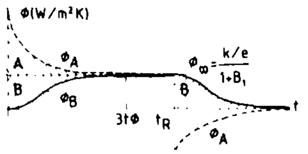
It appears that for very long intervals, *i.e.* when the wind tunnel temperature reduction is infrequent, the energies transferred tend toward very similar values whether the insulation is internal or external, as the energy variation of the metal becomes small with respect to the total energy transfer. But for short intervals or frequent variations, an internal insulator is a very favorable element in the heat balance.

The alternative chosen essentially depends on the wind tunnel utilization: whether great versatility is needed for state variations or if infrequent variations are permissible. This can be evaluated by the "time scale", *i.e.*, the duration of the operations requested and their sequence order, the duration of each test, the temperature variations during the test and between two tests, and the speed with which the change must be made from "cold" to "warm". Here we can see the "test spectrum" idea.

Behaviour of a stingholder and of a cart

The model must, of course, be cooled and reheated (see section 4.6), but what about the stingholder and the cart? If they are not insulated, their temperature will follow the temperature of the wind tunnel and, when any work is to be done on the model, they will have to be kept cold since fast warming would create thermal stresses. If an operation is to be carried out on one of these pieces of equipment, sufficient waiting time is needed. To give an idea, cooling the part of the stingholder located in the test section (3 tonnes) from 300 to 150 K requires 190 MJ, and cooling the cart structure (estimated at 40 tonnes without the lower wall of the test section) requires 2,560 MJ.

We will now examine the energy balances for a stingholder and a cart that are insulated and equipped with an electrical heating system maintaining the metal structures at a constant temperature T_o, when the assembly is placed in a chamber at temperature T, different from T_o, and then returned to the initial conditions after a time t_R. We assume that these operations are, from the thermal point of view, equivalent to applying temperature steps $\pm \Delta T_1 = \pm |T - T_o|$ to the insulator, with a transfer coefficient h between the fluid and the surface. Fig. 31 shows the unit flux variations (per unit surface area and per degree of difference) $\Phi_A(t)$ on the fluid side of the insulator, and $\Phi_B(t)$ on the structure side. In the first approximation, and for sufficiently large t, $\Phi_A(t)$ and $\Phi_B(t)$ are exponentials, one decreasing and the other increasing, with time constant $t\Phi$ and having the same limit value Φ_∞. Letting k be the conductivity of the insulator, e its thickness, $a = k/\rho c$ the diffusivity, the values for $t\Phi$ and Φ_∞ are given in figure 31 along with the maximum electric power P_B to be supplied and the corresponding energy Q_R. We will note that the heating inside must be maintained longer than t_R, which is the reason for integrating to infinity. We show that $Q_B = S\Delta T_1 \Phi_\infty t_R$, regardless of t_R.



$$\Phi_\infty = \frac{k/e}{1+B_1}$$

$$t_1 = \frac{\rho c e^2}{k} = \frac{e^2}{a}$$

$$B_1 = \frac{k}{eh}$$

$$t\Phi = t_1 \frac{1+3B_1}{6(1+B_1)}$$

$$A = \int_0^\infty (\Phi_A(t) - \Phi_\infty)\,dt = \frac{\rho c e}{3(1+B_1)^2} \qquad B = \int_0^\infty (\Phi_\infty - \Phi_B(t))\,dt = \frac{\rho c e(1+3B_1)}{6(1+B_1)^2}$$

Fig. 31 - Study of insulated and heated pieces.

$$\int_0^\infty \Phi_B(t)\,dt = \Phi_\infty t_R - B + B = \Phi_\infty t_R \qquad \int_0^{t_R} \Phi_A(t)\,dt = \Phi_\infty t_R + A$$

$$Q_B = S\,\Delta T_1 \int_0^\infty \Phi_B(t)\,dt = S\,\Delta T_1\,\Phi_\infty t_R = P_B t_R$$

$$Q_A = S\,\Delta T_1 \int_0^{t_R} \Phi_A(t)\,dt = S\,\Delta T_1 (\Phi_\infty t_R + A)$$

$$Q_C = S\,\Delta T_1 \int_{t_R}^\infty \Phi_A(t)\,dt$$

The power to be supplied, in the form of liquid nitrogen, to keep the chamber at temperature T, is QA. The steady state is approximately achieved for $t_R > 3t_\Phi$ (see fig. 31).

When the assembly is returned to temperature T_o, Q_C must be supplied. The atmosphere can do this for free, of course, unless there is some reason for requiring forced convection.

On the stingholder sector with its 4.8 m^2 surface area, only a thin insulator can be used, e.g. 0.01 m thick. We assume the conditions $k = 0.12$ W/m·K, $\rho c = 1.4$ MJ/m^{3}K, $h = 1500$ W/m^{2}K, $\Delta T_1 = 150$ K. We then have $t_1 = 1167$ sec. (20 min.). This means that the structure will not be affected by the temperature for some 1.2 minutes, and that the steady regime will be reached ten minutes after the change. The maximum electric power will be $P_B = 8.5$ KW and the energies Q_A and Q_B, with t_R expressed in minutes, are:

$$Q_B = 0.51\ t_R \text{ (MJ)}$$

$$Q_A = 0.51\ t_R + 3.3 \text{ (MJ)}$$

For a ten-minute test, 5.1 MJ need to be supplied in the form of electricity, and 8.4 MJ in the form of liquid nitrogen, instead of 190 MJ.

For the cart, with its 92 m^2 surface area, a thicker insulator can be used with better characteristics.

Assuming a thickness of 0.1 m and $k = 0.03$ W/mK, $\rho c = 10^5$ J/m^{3}K, $h = 10$ W/m^{2}K and $\Delta T_1 = 150$ K, we have $t_1 = 33,300$ sec. (9 hours). The structure will not be touched for 35 minutes, *i.e.* much more than the ten minutes considered above. The steady regime will be reached only after five hours, and the electric power needed will be only 4 kW.

With t_R in hours we get:

$$Q_B = 14.5\ t_R \text{ (MJ)}$$

$$Q_A = 14.5\ t_R + 43.3 \text{ (MJ)}$$

The cart would then have to spend more than a week in the test section for the heating system to cause an expenditure of nitrogen greater than the cooling of the structure.

The operation of the wind tunnel in relatively short blowdowns (500 rotations of ten to 20 minutes each year) means that the carts are present in the test section, for tests, less than 150 hours per year. Under these conditions, considering the above examples and the existence of the carts, it seems desirable to

leave the test section as soon as the test is terminated, and avoid cooling elements that do not need to be cooled. A relatively thin layer of insulation allows this. *There would also be no reason for cooling these elements before entering them in the test section.*

4.5 - The "Test Section"

The NTF test section area first shown in figure 21 is detailed in figures 32 and 33. The external structure of the center part is lined with internal insulation (Fig. 32). This central part can also be isolated from the rest of the wind tunnel by one door upstream and another downstream, which provides a way of changing the pressure and temperature conditions in the test section without returning the rest of the circuit to atmospheric pressure.

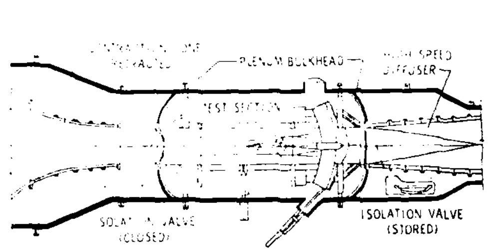


Fig. 32 - Test section and plenumùm isolation system.

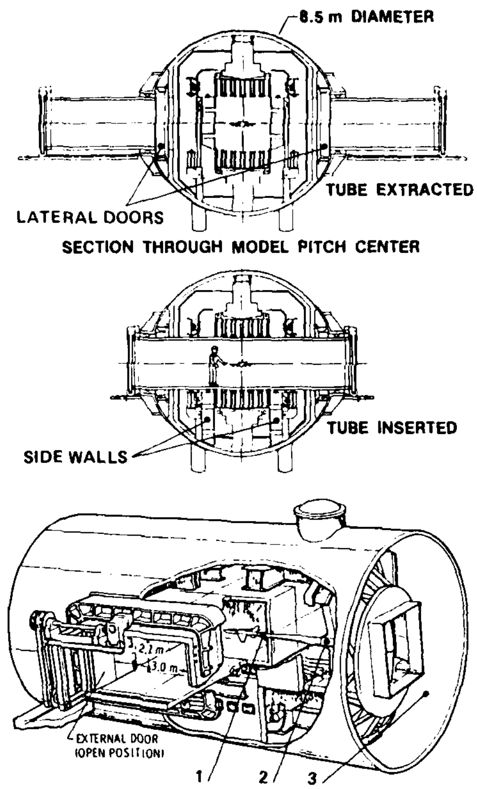


Fig. 33 - Model access system and isometric view of model access system in the inserted position.

According to NASA, the doors pay for themselves in three years by the savings in operational costs. This study is based on examination of a realistic workload including an appropriate distribution of the different types of tests expected [16].

As figure 33 shows, there are three entrance areas:

1) to gain access directly to the model
2) to gain access to the plenum surrounding the test section, where the stingholder is located
3) the remainder of the circuit upstream and downstream of the doors.

Entrance (3) is needed for wind tunnel circuit maintenance, and is unrelated to the test section or to the experimenters' work. However, we will note that the upstream and downstream doors are in this area and that they must be perfectly reliable so as not to affect the test in progress.

Entrance (2) is needed for changing the model or for working on the model electrical or pneumatic connections, which are inside the rear part of the stingholder. The structure then has to be reheated and the plenum filled with dry air. The access time may be as much as five hours.

Entrance (1) is for normal operations on a model during the test. The test section is placed at atmospheric pressure, after closing the upstream and downstream gates (Fig. 32), the test section lateral gates are lowered, the side doors of the plenum (2.7 m · 3.7 m) are unlocked and moved sideways, and the access tubes are entered (Fig. 33). The model can then be reheated so experimenters can work on the model.

In each of the three instances, the changes from cold, dry nitrogen to warm dry nitrogen and then to dry air and humid air are carefully provided for.

Entrance (1) is used for changing the model configuration at the end of one rotation to another model configuration for the next rotation, an operation that takes about two hours. Figure 34 gives the time for the various operations carried out in entrances (2) and (1). As far as entrance (2) is concerned, the thirty-minute conditioning time is for the change to dry air, so a man can work in the tunnel, but not for a return to atmospheric temperature.

FUNCTION	TIME
CONDITION PLENUM	18 min
INSERT TUBES	3 min
CONDITION TUBES/WARM MODEL	37 min
CHANGE/SERVICE MODEL	VARIABLE
PREPARE FOR TUBE EXTRACTION	5 min
RETRACT TUBES	3 min
RETURN TO OPERATING CONDITIONS	18 min
TOTAL	84 min + VARIABLE

COMPONENT/PROCESS	MOTION	ACTUATION TIME	METHOD
CONTRACTION/DIFFUSER	CLAMP/UNCLAMP TRANSLATE	3.5 min	ELECTRO MECHANICAL ACTUATORS
BULKHEAD CLOSURE	POSITION & CLAMP	9.5 min	ELECTRO MECHANICAL ACTUATORS
PLENUM VENTING	BLOWDOWN	3.0 min	
TEST SECTION DOOR LOCKS	ENGAGE/DISENGAGE	0.1 min*	ELECTRO MECHANICAL ACTUATORS
MODEL ANGLE LOCK	ENGAGE/DISENGAGE	0.5 min*	ELECTRO MECHANICAL ACTUATORS
CORNER FILLETS	DISENGAGE/STORE	0.5 min*	ELECTRO-MECHANICAL ACTUATORS
TEST SECTION DOOR	RAISE/LOWER	1.0 min*	HYDRAULIC ACTUATORS
PLENUM CONDITIONING	INBLEED DRY AIR	30.0 min	
PLENUM DOORS	TRANSLATE	2.0 min	ELECTRO-MECHANICAL ACTUATORS

* CAN BE ACCOMPLISHED DURING VENTING OR FILLING

Fig. 34. Access times. Right: zone 2 "plenum" left: zone 1 "model access"

With the test section area arranged this way, the "piece" taken out of the wind tunnel, which can be prepared outside, includes the model, its balance and the sting, as in ONERA's S2MA wind tunnel (see section 3.2). At the NTF, there is a special chamber provided for testing this element in a cryogenic environment. However, the model is entered "warm" in the wind tunnel.

Interchangable carts were chosen for the ETW. The "piece" taken out of the wind tunnel includes the lower part of the test section and the stingholder (or wall mount) supporting the model.

When several carts are used, this arrangement makes it possible to fully prepare several tests outside the test section, while another test is going on inside. The time needed to move the model in and out depends on the speed of the mechanisms.

The preliminary arrangements include an access lock with two gates (Fig. 35). To remove a model, the cart is lowered into the lock and the upper gate is shut. The lock is then depressurized the access lock gate is opened and the cart is removed. It is the cart lift platform that closes the circuit, in the current design (Fig. 36). With one gate upstream of the test section and another downstream, as in the previous case, it would be possible to remove and insert the cart without depressurizing the entire wind tunnel. Without these gates, each cart movement requires a total circuit depressurization.

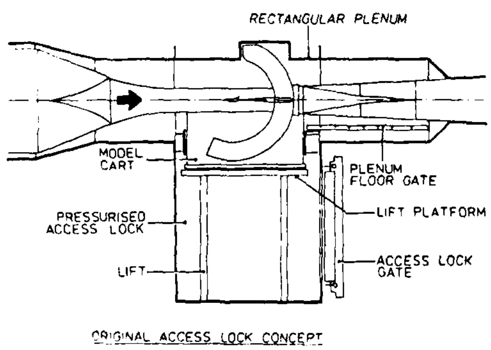


Fig. 35 - E.T.W., original access lock concept.

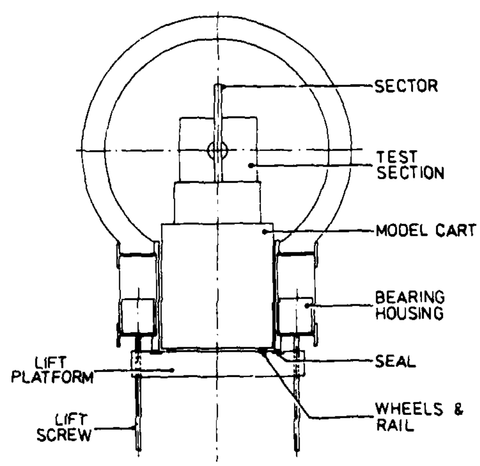


Fig. 36 - E.T.W., new concept.

Once taken out of the test section, the cart can be placed in a temperature conditioning room (TCR), one part of which (the quick change room, or QCR) is only for working on the model. Another room is provided for a preliminary cryogenic test before placing the model in the test section (the variable temperature checkup room, or VTCR) [13].

The model thus enters the wind tunnel test section at the planned test temperature.

We thus note that the cart-type handling system makes it possible to establish the wind tunnel temperature conditions without the cart, using a moving element to replace the cart as a floor and thus close the circuit. We can thus insert a model at a preset temperature in a wind tunnel that is also at the

preset temperature. This wind tunnel conditioning possibility is of greatest advantage when associated with two gates upstream and downstream of the test section, which allow pressure preconditioning.

The moving cart idea has also been adopted for the KKK wind tunnel (Fig. 37). After a test, the cart is lowered into the access lock, which is then separated from the wind tunnel by a horizontal gate. The model is then warmed with dry nitrogen and then with dry air. The access time is estimated to be four hours. For minor changes, the model is moved into a conditioning room in which the reheating cycle is estimated to be twenty minutes [15].

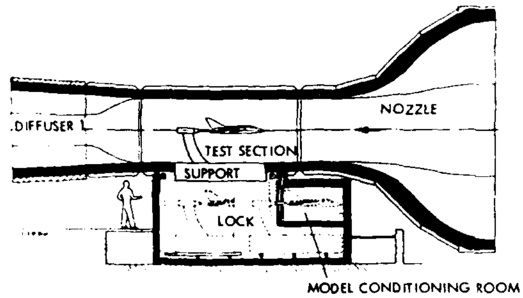


Fig. 37 - K.K.K. Test section, access lock and conditioning room.

4.6 - *Temperature conditioning*

The temperature conditioning of the model should be designed, in accordance with the wind tunnel temperature conditioning, to minimize the thermal gradient effects in the model (stresses and dimensional stability) [22] and to obtain reproducible T_p/T_f conditions (T_p = model skin temperature, T_f = adiabatic friction temperature) [28].

The question of the reproducibility of T_p/T_f and of a tolerable difference $\Delta(T_p/T_f)$ is particularly important for cryogenic wind tunnels and has been treated in many works [29 to 35]. However, no simple criterion can be drawn from the opinions of the various authors. Green has suggested that the model skin temperature should not deviate more than 1% from the adiabatic friction temperature [36].

Considering, in particular, the effect of T_p/T_f on the drag, Johnson allows an 8% difference [29]; but considering those cases where the separation effect can be large, Lynch suggest less than 1% [31] and documents [33 and 34] confirm this point of view.

Reference [34] summarizes clearly the various effects of T_p/T_f position of the boundary layer transition, characteristics of an attached turbulent boundary layer, turbulent boundary layer-shock wave interaction, onset of the separation, extent of the separated areas. Depending on the effect considered, which may produce monotonic or dicontinuous variations for the same difference $\Delta(T_p/T_f)$, it is understandable that the various criteria disagree. Reference [34] concludes that, in general, it could be desirable to set the allowable difference at 1%, and at less than 1% if separations are involved.

For a wind tunnel with relatively short blowdowns like the T2, the wind tunnel and model must be conditioned prior to the test to obtain the desired value for T_p/T_f. As reference [25] describes it, this was successfully done by cooling the model in a flow of cold gaseous nitrogen, with the model placed in "drawer" for rapid entrance into the wind tunnel.

The *Douglas* company experiment for the 1-foot and 4-foot CWTs have shown that it is nearly impossible to cool the model correctly by projection of liquid nitrogen. Moreover, the time required to stabilize the model temperature in the test section flow would increase the cost of operating a large cryogenic wind tunnel, with its "conr ous" type of operation, which is in fact a kind of long blowdown. This is why it seems reasonable to suggest that the model be conditioned by a cold gaseous nitrogen flow in an auxiliary circuit outside.

5 - CONCLUSION

There are two difficulties in applying the idea of productivity to large wind tunnels: evaluating the quality of the product (test results) and comparing costs, which depend on very different price structures from one installation to the next.

In this application to cryogenic wind tunnels, we have attempted to show the particularities of these wind tunnels, *e.g.*, the "long-blowdown" concept, which we attempt to make as short as possible to reduce the expenditure of liquid nitrogen.

Our examination of what seem to be most important points can help guide the designer. The discussion shows that the use of a cryogenic wind tunnel demands that the users thoroughly study the test program beforehand and dovetail the successive configurations as best possible.

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THE T2 CRYOGENIC INDUCTION TUNNEL IN TOULOUSE

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ABSTRACT

This paper summarizes the main results obtained by the experimental activity at the ONERA/CERT T2 induction tunnel in Toulouse since it was converted for cryogenic operation in 1981. It describes the main characteristics of this facility, operating by short pressurized transonic runs driven by induction, with a test section equipped with two self-adapting walls and its adaptation to cold flows: internal thermal insulation, cooling by injection of liquid nitrogen, system for precooling profile models and introducing them in the test section. The following subjects concerning cryogenic operation are then discussed: pressure and temperature fluctuations, thermal behavior of the walls, transverse temperature distributions in the flow, thermal equilibrium of a profile with the fluid, condensation phenomena in the cold flow and problems of particles. Finally, the test results at *high Reynolds number conducted on a CAST 7 profile with* a 150 mm chord are given.

NOTATIONS

M	Mach number of the flow in the test section
P_t	stagnation pressure of the flow in the test section
T_t, T_{TS}	stagnation temperature of the flow in the test section
P_{tj}	stagnation pressure of the driving jets
$\dot m_j$	driving air mass flow
$\dot m_{LN_2}$	cooling liquid nitrogen mass flow
$\dot m_{TS}$	mass flow of the flow in the test section
S_e	discharge cross section
T	absolute temperature
t	time
X	abscissa in a direction parallel to the flow
Y	abscissa in a direction normal to the flow, following the profile span
$T_{t\ probe}$, $P_{t\ probe}$	local stagnation temperature and pressure measured by a probe
T_W, T_{model}	wall temperature
T_{AW}	adiabatic wall temperature
r	recovery factor
$\gamma = \frac{C_P}{C_V}$	ratio of specific heats at constant volume and pressure ($\gamma = 1.4$)
U	flow velocity in the test section
q	dynamic pressure in the test section
f	frequency
$n = f\frac{H}{U}$	reduced frequency. H is the test section height
$P' = P - P_{mean}$	fluctuating components of static
$T'_t = T_t - T_{t\ mean}$	pressure and stagnation temperature
$\overline{X}$	mean over time of fluctuating value X
C, X/C	profile chord and relative abscissa along the chord measured from the leading edge
M_l	local Mach number on the profile
R_{eC}	Reynolds number based on the chord

α and C_L, C_D	angle of attack of the profile and lift and drag coefficients
Fixed T.	test with tripped transition
Free T.	and test with free transition

1. INTRODUCTION

The T2 transonic induction tunnel, with a 0.4 x 0.4 m² test section which can be pressurized up to 5 bars, has been in operation since 1975 at the Centre d'Etudes et de Recherches of the ONERA in Toulouse.

This facility was initially a 1:10 scale model of a large wind tunnel proposed by ONERA in the framework of the European LEHRT (Large European High Reynolds Tunnel) project. The purpose of this project was to build a transonic wind tunnel where the Reynolds number in flight could be approached by pressurizing the flow and by relatively large model size. The project also included the achievement of good flow qualities in the test section and in particular a low aerodynamic noise level. The two other main proposals for the LEHRT were:

- Ludwieg Tube by DFVLR (Germany)
- Evans Clean Tunnel by RAE (Great Britain).

The induction consists of driving the fluid in the tunnel by high velocity, high pressure air jets Ref. 1). The T2 system is designed to operate by short runs, of a duration of approximately 1 minute, mainly to limit the size of the high pressure drive air receiver.

The first design, development and qualification works on the tunnel made it possible to achieve a low turbulence level, compatible with the severe requirements of the LEHRT project.

In addition, the test section was equipped with two flexible walls positionned by computer during the test to produce the infinite field condition for 2D flows around airfoil profiles.

The concept of a cryogenic wind tunnel has imposed itself as a very promising solution to achieve the in-flight Reynolds number: the increase in the Reynolds number per meter is obtained by decreasing the temperature and thereby the viscosity of the flow. This solution can possibly be combined with pressurized operation. ONERA then decided to convert the T2 induction tunnel in order to rapidly have a cryogenic test facility.

This paper endeavours to summarize the data and important results obtained by the experimental activity developed on the T2 induction tunnel in cryogenics since its conversion in 1981.

In the first part, the main characteristics of the system and its cryogenic runs are described. The following subjects are then discussed: pressure and temperature fluctuations in cryogenic state, thermal behavior of the wind tunnel walls, transverse temperature distributions in the cold flow, thermal behavior of the model, condensation phenomena in the flow and problems of particles, and finally, the results of testing conducted at high Reynolds number on a CAST 7 profile with a 150 mm chord. In conclusion, the improvements and projects under consideration to continue cryogenic operation of T2 are also mentioned.

2. DESCRIPTION OF THE FACILITY

2.1. The Initial Induction tunnel and Its Cryogenic Adaptation

The figure 1 is a general schematic diagram of the wind tunnel and its ancillary equipment.

A stilling chamber, with a cross section of 1.8 x 1.8 m², equipped with a dust filter, a honeycomb and screens, supplies the test section through a convergent with a contraction ratio of 20.

The test section, 0.37 m high and 0.39 m wide, includes a throat in the downstream section which regulates the test Mach number for M > 0.6. A return leg with several diffusers closes the wind tunnel.

The induction drive is in the first corner downstream of the test section: this corner is provided with seven hollow vanes supplied with high pressure air, which output the drive jets at their trailing edge (figure 2). Each vane includes 14 small internal nozzles wich can be supplied independently in groups and which set the Mach number at the jet outlet at M = 1.6. The downstream section of this corner forms a mixing chamber.

The drive air flow is characterized by parameter Ptj, the stagnation pressure measured in the vanes. It is controlled by a proportional valve (figure 3). A 45 m³ dried air receiver, where the air is stored at 80 bars, supplies the facility via a heater.

The necessary exhaust, with a flow rate equal to the drive air flow rate, is located just upstream of the injector corner. It is achieved by pressurization of the wind tunnel through the porous bronze walls of a rectangular channel which acts as first aerodynamic diffuser between the test section and the inductor corner.

Cryogenic conversion of the initial wind tunnel, as described briefly above, can be summarized by two main points, plus a considerable increase in the control and indication facilities. These solutions were selected after feasibility studies on the pilot T'2 facility, a 1:4 scale model of T2.

- The flow is cooled by direct injection of liquid nitrogen in the return leg, with the inductor air jets remaining at ambient temperature. It would have been possible to consider cooling of the inductor air jets, but the solution selected is simpler to implement and has the advantage of increasing the efficiency of the induction drive when the drive jet temperature is above that of the fluid driven.
- The tunnel is provided with internal thermal insulation, required by operation in short runs and by the pressurizable circuit made of ordinary steel, brittle at low temperatures. During the short time of the run, it is then possible to rapidly cool the flow alone, with the metallic

structure remaining at ambient temperature: a considerable thermal gradient exists in the thickness of the insulation and the fluxes are sufficiently small for the internal skin temperature to be close to the adiabatic wall skin temperature.

The liquid nitrogen is injected perpendicularly to the flow at the wall of an element immediately downstream of the inductor corner: 32 injectors with stepped flow rates are distributed on two circles, each supplied by its own solenoid valve to allow digital regulation of the liquid nitrogen flow rate (figure [illegible]).

Locating the liquid nitrogen injection in an area of high velocity flow is conducive to vaporization and mixing. In addition, the maximum upstream distance of the test section allows a satisfactory time for the same thermal uniformization phenomena.

A [illegible] m test tank pressurized at approximately 15 bars supplies the injector . For a given flow rate, the use of an injector with a small cross section and a high injection pressure considerably reduces the problems of priming the nozzles. The system is also provided with drains for cooling before the test.

The exhaust system which, in cryogenic operating mode, eliminates the sum of the drive air and liquid nitrogen flows, is not modified. The ducts downstream of the porous walls are provided with a metering system (figure 3). The fluid exhausted and vented to atmosphere follows both a main duct provided with a continuous analog valve which is theoretically positioned before the test and an auxiliary duct divided into seven parallel branches of stepped cross sections, each with a solenoid valve, allowing digital regulation of this part of the flow rate.

Selection of the thermal insulations and attachment mode was a major task which gave rise to many tests.

Adhesive bonding appeared to be the simplest and most appropriate method of attachment to avoid thermal bridges between the flow and the steel walls.

From a thermal standpoint, performing insulations are those with a low conductivity and heat capacity. However, other factors must be considered: the surface condition of the insulation, the mechanical capability of the material and its bonding to withstand the temperature and pressure cycles.

Schematically, the internal insulation of the wind tunnel includes:

In the low velocity parts, i.e. the return leg and stilling chamber, 10 mm of polyurethane locally reinforced by kevlar fabric. The polyurethane foam is a material with very low conductivity and heat capacity, but with a slightly rough surface. The surface of the polyurethane is covered with kevlar only in a small part of the return leg, immediately downstream of the liquid nitrogen injection.

In the high velocity parts, i.e. the test section and inductor corner, 5 mm of agglomerated cork of the Norcoat type. This insulation is less performing but has a good surface condition.

Certain parts of the system: air injection vanes, liquid nitrogen injection element, are provided with special insulation. The insulation of the circuit is described in greater detail in reference 7.

The new or modified parts of metallic circuit (liquid nitrogen injection element, exhaust) were made of stainless steel which preserves its mechanical properties at low temperatures.

For a dual purpose of measurement and safety, the entire wind tunnel circuit is permanently fitted with some hundred thermocouples which give the internal skin temperature, the temperature of the metallic structure, and the flow temperature in the stilling chamber by means of a transverse grid of 25 thermocouples. The thermocouples in the center of the grid determine the reference stagnation temperature T_t.

Finally, the low points of the circuit are equipped with traps which detect and eliminate any collected liquid nitrogen.

For more detailed information on operation at room temperature and the cryogenic conversion of T2, refer to the notes mentioned in references 2 and 6.

The scope of use of the wind tunnel covers a range of Mach numbers from $M = 0.3$ to $M = 1$. The stagnation pressure can be varied from a minimum value of approximately 1.6 bars up to 5 bars.

The facility is actually generally used in the low transonic range from $M = 0.6$ to $M = 0.9$ and at low temperature, a stagnation pressure level of $P_t = 3.1$ bars has not been exceeded.

According to the results described in Section 5.1, the operating limit at low temperatures depends on the pressure level and the Mach number. It can be retained that it is approximately $T_t = 100$ K at transonic velocity for stagnation pressures not exceeding 3 bars. The lowest stagnation temperature achieved is $T_t = 95$ K, during a test conducted with the test section empty at $M = 0.8$ and $P_t = 2$ bars.

As concerns testing on the CAST 7 profile with a 150 mm chord, many tests were carried out at T_t = 105 K or 110 K, $P_t = 2.5$ bars and $M = 0.76$, giving a Reynolds number based on the chord of approximately $Re_c = 20 \times 10^6$.

With the CAST 10 profile which has a 180 mm chord, the Reynolds number $Re_c = 30 \times 10^6$ was achieved for $T_t = 110$ K, $P_t = 3.1$ bars and $M = 0.76$.

2.2. Cryogenic Testing on Profiles

2.2.1. Model Precooling and Introduction System

The need for satisfactory thermal equilibrium between the model and flow strongly influenced the cryogenic test procedure used in the T2 tunnel. In effect, cooling a relatively bulky metal profile initially at room temperature, by the flow in the test section, requires at least 150 [illegible], which exceeded the maximum time provided for a run. As it was initially decided to use models with a conventional structure in T2, the requirement for precooling was imposed.

It should however be noted that the idea which arose on this occasion to produce models with a lower thermal inertia has not been dropped for the future, in particular as concerns metal profiles with a relatively thin skin.

An ancillary precooling system using a cold gaseous nitrogen stream was designed and built (figure [illegible]) for profile testing. It includes a precooling box mounted on one of the lateral doors of the test section and a translation system which supports the profile by one of its heels and allows it to be rapidly introduced in the test section. A locking system is provided on the opposite door of the test section to correctly define the geometric position of the model. Mounting on the doors is by means of a system with two windows, which sets the profile angle of attack by rotating the assembly.

The profile is introduced in the test section during a run when the initial flow at a low Mach number and low pressure has reached the nominal test temperature (section 2.2.3.).

An ancillary system produces a cold gas flow around the profile in the precooling box. The assembly forms a small continuous wind tunnel with a fan, cooled by injection of liquid nitrogen and operating at atmospheric pressure. The velocity on the profile is approximately 50 m/s. An example of precooling of the CAST 7 profile with a 150 mm chord for a test at T_t = 150 K is illustrated in the figure 6. Precooling lasts about 10 minutes and a regulation program holds one of the profile temperatures at the selected value by action on the injected liquid nitrogen flow, with an accuracy of approximately ± 0.5 K.

2.2.2. Self-Adapting Walls

Before and independently of the cryogenic conversion of the wind tunnel, the T2 test section was equipped with two flexible walls at the top and bottom, each positioned by 16 actuators, and a two-dimensional adaptation system was developed for profile testing/ref. 11 and 12/.

The purpose consists of recreating a flow with an infinite field around the profile by the form of the walls: the adapted form is theoretically a streamline generated in the same location by the profile in infinite field, within the boundary layers of the wall.

The iterative process used to achieve this adapted form is based on the longitudinal pressure distribution on the deformable wall: the measured distribution is compared with a theoretical distribution computed for the same streamline (real wall) in a fictitious infinite field. The adaptation is complete when the two distributions converge. In the event of a difference, the wall is positioned on a new streamline estimated by relaxation. The method also takes into account the development of boundary layers on the walls. The process rapidly converges and the adapted form is obtained after a few iterations. With the present system the duration of an iteration is approximately 7 s (measurement, computation, positioning).

The same adaptation technique is also used in cryogenic operation. The deformable steel walls are simply replaced by 1.3 mm thick Invar walls. Each panel is 0.39 cm wide and 1.32 m long (figure 7). The 16 transverse stiffeners on which the positioning device operates are welded to the panel by electron beam. A set of slots in the stiffeners 1 mm under the wall creates a thermal barrier with the mechanical positioning system. Each wall is equipped with 96 brazed pressure taps, 61 of which are on the longitudinal centerline. Upstream, the walls are attached by flush mounting and are tangent to the manifold outlet. The downstream throat of the test section is equipped with two mobile panels which ensure correct interfacing with the wall ends. Finally, four teflon seals provide the lateral seal between the deformable walls and the fixed vertical walls clad with Norcoat cork.

The thermal inertia of the Invar panels is sufficiently low to allow them to be cooled by the cryogenic flow before the useful part of the run. The figure 17 gives an example of cooling of these walls during a test at M = 0.7 and T_t = 150 K.

Invar was obviously selected for its low thermal expansion coefficient Satisfactory mechanical operation of these walls in cryogenic state was observed during many tests on the CAST 7 profile, C = 150 mm, and the CAST 10 profile, C = 180 mm.

2.2.3. Execution of the Cryogenic Run

The regulation system developed for the T2 wind tunnel for cryogenic operation is described in the note mentioned in Reference 10. Only the main features are recalled below, describing the three phases of execution of a run. Since 1982, this method has benefited from many improvements and detail modifications.

The parameters of the flow, the Mach number M in the test section, the stagnation pressure P_t and temperature T_t are controlled by action on three control parameters : the drive air flow rate q_i, the liquid nitrogen flow rate q_{LN2} and the exhaust cross section S_e, to which must be added the cross section of the sonic throat which sets the Mach number in stabilized state and which is positioned before the test. During the run, the tunnel is controlled by an HP 1000 minicomputer which uses simple models of the wind tunnel with the temperature control separate from the pressure control. A second computer handles control of the measurement and exploration systems, data acquisition and adapting of the walls.

The figure 4 shows the variation in the flow and control parameters during a typical run at M = 0.7, T_t = 150 K and P_t = 3 bars.

The cryogenic test can be started when the profile is at the equilibrium temperature corresponding to the stagnation temperature of the test and ready to be introduced in the test section. The throat opening corresponds to the Mach number of the test. On the exhaust circuit, the system of digital control valves is completely open and the continuous valve is in a position compatible with the nominal stagnation pressure.

The first phase of the cryogenic run consists of setting up a flow with a low Mach number, M = 0.3, and a low stagnation pressure, P_t = 1.1 bars, at the nominal test temperature. The wind tunnel is started at room temperature. Under these conditions, the throat is not sonic. The computer injects a liquid nitrogen flow rate equal to several times the value required to cool the drive air flow. The flow temperature drops rapidly and when the computer predicts that it is going to reach the setpoint, it gradually decreases the liquid nitrogen flow rate to finally enter closed loop regulation of the measured stagnation temperature T_t. When the flow is stabilized at nominal temperature, the profile is introduced in the test section and locked in place.

The second phase consists of simultaneously increasing the Mach number and stagnation pressure up to the nominal values, while holding the flow temperature roughly constant. At the beginning of this phase, the regulation valves close on the exhaust circuit and the drive air flow rate is increased linearly

up to its final value which is sufficient to obtain a sonic throat and obtain the desired pressure, considering the opening of the continuous exhaust valve. The stagnation pressure increases rapidly and when it reaches the nominal value, its closed loop regulation by the exhaust valves begins. This phase ends when the stagnation pressure is stabilized. During this phase, the temperature is maintained independently by a liquid nitrogen flow rate computed to cool the drive air flow and compensate for the compression effect.

During the third phase, the operating parameters are held at the nominal test values for the time required to make the aerodynamic measurements. The pressure regulation by the exhaust cross section is simultaneous with the closed loop temperature regulation by the liquid nitrogen flow rate which is recovered. During this phase, the stagnation temperature is stable, remaining generally within a 1 K bandwidth.

The iterative wall adapting process is initiated at the start of this last phase, for testing on profiles. Valid aerodynamic measurements are made when the adaptation is achieved (wall pressure distribution on the profile during the last iteration, followed by exploration of the wake in the case of tests on CAST 7, C = 150 mm).

The run is stopped by cutting off the liquid nitrogen injection and opening the exhaust before reducing the drive air flow rate.

2.2.4. Cryogenic Operating Performance

Among the first tests conducted after conversion of the wind tunnel, a series of runs at various temperature levels made it possible to determine the performance characteristics in cryogenic operating mode, i.e. the influence of the temperature on the drive effect of the drive air jets and the liquid nitrogen flow rate required to obtain a given stagnation temperature.

For tests at a Mach number of M = 0.8 in the test section and at a stagnation pressure P_t = 1.8 bars, the variation in the ratios of the drive air flow rate q_i and the injected liquid nitrogen flow rate q_{LN_2} to mass flow rate in the test section q_{TS} during the final stabilized phase of the test are shown in the figures 8 and 9 respectively.

It is observed that the ratio Q_i/q_{TS} decreases as the operating temperature decreases, which confirms the increase in the induction efficiency predicted by the injector theory, as the temperature ratio between the drive fluid and driven fluid T_{ti}/T_{tTS} increases. The black spot on the Figure 8 for operation at room temperature represents the induction efficiency before conversion of the circuit: the slight decrease in performance recorded is explained by a moderate increase in the pressure loss of the circuit due to the presence of the internal thermal insulation.

The ratio of the liquid nitrogen flow rate to the test section flow rate is obviously zero at room temperature. It increases practically linearly as the operating temperature decreases. At level T_t = 120 K, the liquid nitrogen flow rate represents approximately 8 percent of the flow rate in the test section. The dashed line curve in the Figure 9 represents the ratio of a liquid nitrogen flow rate, computed to cool only the drive air flow rate of the test at nominal temperature, to the test section flow rate. The difference between the experimental curve and the computed curve gives the order of magnitude of the thermal losses of the circuit: from zero at room temperature, they increase as the temperature decreases and represent approximately 15 percent of the total liquid nitrogen flow rate for T_t = 120 K, which confirms the efficiency of the internal insulation.

It should also be noted that at low operating temperatures, the drive air and liquid nitrogen flow rates are of the same order of magnitude (8 to 10% of q_{TS}), i.e. approximately 10 Kg/s for a flow rate in the test section q_{TS} = 100 kg/s (M = 0.8, P_t = 2 bars, T_t = 120 K).

2.2.5. Safety and Protection

Personnel safety and protection of the facility are ensured by the action of four independent systems:

- an operator monitors the test controlled by the computer on a control panel and can stop it at any time
- the control and monitoring panel, with its own set of transducers and relays, continuously monitors a wide range of parameters : wind tunnel pressure, presence of liquid nitrogen in the system traps, oxygen content of the air in the room, locking of the room doors, etc and can stop the test.
- the control and regulation computer with its own acquisition system is programmed to stop the run on occurrence of certain conditions deemed hazardous (temperature too low, pressure too high) or when a malfunction is detected in the wind tunnel.
- a set of passive devices such as relief valves and diaphragms form the last level of protection.

As concerns the problem of personnel safety when working in the wind tunnel, the following attitude was taken, in particular after the first test campaigns on profiles. The best contribution to safety is a set of reliable and well designed systems whose operation was developed, refined and proven before use in the wind tunnel. The safety conditions are optimum when the normal test procedure can be chronologically followed without interruption. However, when preparation of a test or the run itself is interrupted by minor malfunctions, more hazardous conditions are very likely to occur: the safety settings are not as closely complied with, the procedure for restart of an interrupted test is generally fraught with pitfalls, the risk of human error increases and the wait may cause other failures (valves stuck by the cold, etc.).

The dissipation of the fluid (approximately 89% N_2 and 11% O_2) exhausted to atmosphere also created a safety problem. A stack 10 meters high made it possible to decrease stagnation of the cloud of cold oxygen-depleted gas around the exhaust point which is near a parking lot. Fortunately, there is often wind.

2.3. History of Cryogenic Activity at the T2 Wind Tunnel

The first feasibility tests which led to the decision to convert the T2 wind tunnel for cryogenic operation were conducted on the T'2 pilot induction tunnel in 1977 and 1978. The conversion works on the T2 facility were carried out in 1981 and the first cryogenic runs were carried out in September of the same year.

The run procedure and the method for real time control of the wind tunnel by minicomputer were developed in 198[illegible] after a preliminary experimental study on T'2.

This procedure was used during an initial systematic cryogenic test campaign without model designed to analyze the flow qualities, conducted in September 198[illegible]: measurement of temperature and pressure fluctuations, transverse temperature distribution in the test section, detection of condensed particles in the flow using a laser system.

The system for precooling and introducing wing profiles was designed, built and completed in 1982 and 1983. The adapting cryogenic Invar walls were made in 1983, as well as the first CAST 7 cryogenic profile with a 1[illegible] mm chord.

The first cryogenic tests on models were conducted with this profile and with the new self-adapting walls in December 1983. This campaign extended to February and March 1984.

Feasibility tests, designed to test operation of a balance for cryogenic tests, with a schematic model were conducted in September 1984.

Finally, cryogenic tests on a CAST 10 profile with a 180 mm chord, made in 1984, were conducted in November and December 1984.

It should also be mentioned that a small continuous cryogenic wind tunnel, T'3, with blower is widely used to develop the cryogenic instrumentation used in T2: thermocouple temperature probes, pressure probes with Kulite transducers, optical particle detection system, etc. Presently, cryogenic testing and maintenance of the facility occupy approximately six months a year, the remainder of the time being devoted to test programs at room temperature.

Finally, the Toulouse Research Center benefits from active general contribution by the Direction des Grands Moyens d'Essais and ONERA on the cryogenic programs conducted in T2, in particular engineering (building of models, thermal insulation and materials, design office problems).

3. Fluctuations in the cryogenic flow

3.1. Instrumentation and General Considerations

The fluctuations in the stagnation temperature are measured by the variations in resistance of a tungsten wire [illegible] microns in diameter, supplied at a low constant current, i = [illegible] mA. This wire is located orthogonally to the flow, in the center of the stilling chamber just upstream of the manifold. Its very low thermal inertia means that its temperature is very close to that of the flow, allowing temperature fluctuations to be monitored for frequencies not exceeding 50 Hz. There is a linear relationship determined by calibration between the resistance and temperature of the wire. The wire resistance is measured from the voltage across it.

The pressure fluctuations are measured on one of the lateral walls of the test section by a miniature Kulite transducer. The transducer installation (figure 10) attempts to reduce to a minimum the volume between the static pressure tap flush with the wall and the transducer membrane so as to obtain a wide bandwidth, which reaches a frequency of approximately 10 kHz. An O-ring seals the measurement volume and, with a teflon ring, holds the transducer in position while preventing mechanical stresses on it.

It is recalled that such a transducer can be used even when its own temperature varies: it preserves a linear response as a function of the pressure, but its sensitivity varies slightly with temperature /Ref. 3/. In the case of this setup, we have observed that the transducer temperature, measured from its impedance, drifts only by some 40 degrees during a run at T_t = 120 K. The resulting variation in sensitivity, approximately 3.5 percent, can be considered negligible for measurement of the fluctuation level.

The temperature and pressure fluctuations are analyzed during the final stabilized phase of the run, as a function of the test temperature; the Mach number is M = 0.83, in the test section and the stagnation pressure, P_t = [illegible] bars, with the downstream throat sonic.

3.2. Static Pressure Fluctuations on the Test Section Wall

The measured pressure signal is digitized by the acquisition system at N point per second after analog filtering eliminating frequencies above N/2. The fluctuations are analyzed by frequency segments (N = 100, 1000 and 10000 points per second). A program using the Fourier transform computes the mean energy spectrum of the signal. The values are made dimensionless using the reduced frequency n = f.H/U (H: height of the test section; U: flow velocity) and the reduced fluctuation energy $F_p(n)$ such that : $\int_c^{n_{max}} F_p(n)dn = \overline{p'^2}/q^2$ where q is dynamic pressure: $q = 1/2\ (\rho U^2)$. The spectra given in the figures are actually the mean of several spectra over different time intervals.

This method, of which the main points were recalled above, was developed to qualify T2 at room temperature in the framework of the LEHRT project/Ref. 2/. It is used here with cryogenic flows.

The reduced spectra of static pressure fluctuations in the test section are illustrated in the Figure 11 for operating temperatures of 295 K, 150 K and 120 K. The reduced fluctuation amplitude $\sqrt{nF_p(n)}$ is represented linearly on the ordinate. The reduced frequency n on the abscissa is given on a logarithmic scale.

The three frequency ranges, F < 40 Hz, F < 400 Hz and F < 4 000 Hz, are analyzed at room temperature. The spectrum determined has a very low level at low frequencies ($\sqrt{nF_p(n)} \simeq 0.3 \times 10^{-3}$ for $n < 10^{-[illegible]}$) with a gradual increase in the fluctuation level for higher frequencies, corresponding to the noise of the turbulent boundary layers on the wall. The spectrum is very similar to that measured before the cryogenic conversion of the circuit and remains compatible with the severe requirements of the LEHRT project.

The spectra determined at levels T_t = 150 K and T_t = 120 K have a form which is identical to that of spectrum at room temperature, but exhibit an increase in the fluctuation level for all the frequencies analyzed ($\sqrt{nF_p(n)} \simeq 0.5 \times 10^{-3}$ for $n < 10^{-1}$ and T_t = 120 K).

It is probable that this phenomenon, which remains relatively moderate, is related to the cryogenic operation and is correlated with the increase in thermal turbulence, as will be described.

3.3. Total Temperature Fluctuations

The same measurement processing and spectrum computation method is used as for pressure fluctuations. The reduced fluctuation energy $F_T(n)$ is defined by $\int_0^{n_{max}} F_T(n)dn = \overline{T_t'^2}/T_t$. The figure 12 shows the reduced amplitude $\sqrt{nF_T(n)}$ as a function of the reduced frequency n for operating temperatures T_t = 295 K, 150 K, 120 K.

Acquisitions were carried out at N = 100 points per second (F = 40 Hz) and N = 1000 points per second (F = 400 Hz). In fact, the fluctuations are correctly measured for low frequencies up to a value of approximately 50 Hz ($n \approx 10^{-2}$) corresponding to the time constant of the 9-micron wire (heat exchange and thermal inertia). The 40 Hz cutoff frequency of the lowpass analog filter also appears on the spectra obtained from the acquisitions at 100 points per second.

In reduced form, the spectrum exhibits a roughly constant level from low frequencies up to $n = 10^{-1}$ and this level increases regularly as the test temperature decreases.

The root mean square value (rms) of the temperature fluctuation over the same frequency domain is shown in the figure 13 as a function of the operating temperature . A substantial increase in the relative value $\sqrt{\overline{T_t'^2}}/T_t$ can be observed when the temperature decreases due both to the decrease in term T_t and to the increase in the absolute value of the fluctuation level, $\sqrt{\overline{T_t'^2}}$ which increases from 0.03 K at room temperature to a value of approximately 0.14 K for T_t = 100 K.

These temperature fluctuations are obviously related to the cryogenic operation. They can be attributed to an imperfect mixing of the drive air at room temperature with the driven cryogenic flow, a lack of uniformity in the cooling by spraying of liquid nitrogen and the discontinuous temperature regulation process for variations at very low frequency.

In conclusion, it appears important not to neglect this increase in fluctuation in the cryogenic state when interpreting the tests on models. The behavior of the boundary layer on the model, in particular in cases of free transition, is sensitive to the noise level of the flow which is a cause for dissimilarity between the wind tunnel and actual flight /Ref.13/.

4. THERMAL PHENOMENA

4.1. *Temperature Measurements*

The temperatures are generally measured by commercially available copper-constantan thermocouples whose junction is cast in a fiber and resin plate 0.15 mm thick of small size (4 x 8 mm). These thermocouples are equipped with their own copper-constantan wires, sufficiently long for connection to the copper-copper sensing wires external to the wind tunnel, placed in thermally controlled enclosures at a reference temperature (generally 0 Celcius). The response time of these plates, which depends on heat exchange with the medium, is relatively small: in a flow of a few tens of meters per second, they allow measurements up to a frequency of approximately 5 Hz.

These plates, simply bonded, are fitted on the internal insulated walls and the external metal walls of the wind tunnel. This simple technique for wall temperature measurements cannot however be applied to all cases, as the plate must always be considered a relatively insulating film. This method is in particular unsuitable for the surface of a metal model in thermal disequilibrium with the flow.

The simplest setup to measure the flow temperature consists of locating the thermocouple plate parallel to the direction of the wind. It is held downstream by a hardwood support leaving the vicinity of the junction free (Fig.14). The relatively low conductivity of wood makes the thermal influence of the supports, slower to reach thermal equilibrium, negligible in the measurement.

Such a probe rapidly reaches a temperature of equilibrium with the flow, T_f (friction temperature) which is related to the stagnation temperature by the relation: $T_f/T_t = (1 + r\,(\frac{\gamma-1}{2})M^2)/(1 + (\frac{\gamma-1}{2})M^2)$ which involves the local Mach number M and a recovery factor r of the order of 0.8 to 0.9, determined by calibration and which depends on the boundary layer flow on the probe.

In the stilling chamber, 25 probes of this type are distributed on a grid with a square mesh of 0.3 x 0.3 m², just upstream of the manifold, and directly measure the stagnation temperature distribution, considering the low flow speed.

Three thermocouple probes of the same type are fitted on a mobile rake with three teeth, which was mounted in the center of the upstream part of the test section during the flow quality analysis campaign. Each of the three measurement points also includes a total pressure probe. Complete transverse explorations of the test section are thus obtained by moving the rake (figure 18).

However, the uncertainty as to the real value of the recovery factor r of such a probe, in particular in the lateral parts of the test section where there are transverse temperature and velocity gradients and where the turbulence of the flow increases led us to making total temperature probes (*Figure 15*). In this case, the thermocouple plate is contained in a hollow hardwood shell designed to stop the flow which penetrates through a slot upstream of the thermocouple. A small diameter hole is provided downstream to ensure a ventilation flow through the cavity.

Such a total temperature probe associated with a total pressure probe is used for measurements supplementing the explorations of the mobile rake, in the vicinity of one of the walls, in the same part of the test section (figure 19).

Another total temperature probe is used for transverse exploration of the 150 mm chord CAST 7 profile wake one half chord back of the trailing edge. In this case it is associated with two pressure probes: one total pressure probe and one static pressure probe (Figure 25).

To measure the skin temperature of the steel CAST 7 profile with sufficient accuracy, copper-constantan thermocouples of a different design are used. The junction, reduced to a minimum volume, is housed 1 mm under the model surface in a well machined in the internal surface of this part of the profile: the model is made in three parts assembled by welding, and the hollow center part lined with nickel felt allows the thermocouples wires and pressure tubes to be led to one of the heels (Section 6.1. and Figure 29). The profile is so equipped with eighteen thermocouples, ten of which are located chordwise on the lower surface and upper surface of a center section and the others spanwise.

The theoretical temperature difference between the profile skin and the metal at a depth of 1 mm is negligible under normal test conditions. For a model within a few degrees of thermal equilibrium with the

transonic flow, it is approximately one tenth of a degree, considering the conductivity of steel.

4.2. Thermal Behavior of the Walls

The figure 16 gives an example of cooling of the elements of the external metal structure during a test conducted at M = 0.8 and a stagnation temperature T_t = 100 K, the latter being held for a relatively long time of 100 s. The thermocouples measure the variations which are significant but of small amplitude, demonstrating the efficiency of the internal insulation.

The second diffuser, made of stainless steel and located immediately downstream of the liquid nitrogen injection, is the element which is cooled the most : its temperature decreases by approximately 7 K during the test.

This decrease is approximately 2 K for the elements of the circuit at high velocity (test section and inductor corner) and about 1 degree for the elements in the low velocity return line.

The dispersion in the initial temperatures of the various elements of the circuit is due to repetition of the runs and to the cold air which tends to accumulate in the pit containing the return line.

When cooling the flow at the start of a cryogenic test, the surface temperature of the internal insulated wall follows that of the flow with a delay of approximately 15 seconds, reaching a level within a few degrees of the final stagnation temperature. This difference is approximately equal to 10 to 12 K in the test section for operating temperatures from T_t = 100 K to T_t = 150 K. The analysis of the transverse temperature distribution in the fluid shows that it is mainly related to the existence of a zone of warmer fluid near the walls, which extends largely beyond the dynamic boundary layer.

The same final temperature difference of about ten degrees between the wall and the flow is also observed in the case of the metal self-adapting walls. Their cooling by the fluid (Figure 17) is slower, but considering this systematic difference, it is completed by the start of the adaptation and measurement phase.

4.3. Transverse Temperature Distributions

The tests were conducted at a stagnation pressure of 2 bars and at Mach numbers of 0.8 and 0.55 in the test section. Those for which temperature exploration was conducted in the test section cover a range of temperatures from T_t = 105 K to room temperature. The distribution in the stilling chamber and the wall temperatures along the test section (Fig.20), continuously measured, are available for a larger number of cryogenic tests down to an operating level T_t = 95 K.

In the stilling chamber, a practically uniform temperature distribution, within a degree, is obtained by the start of the final stabilized phase of the test, on the 1.2 x 1.2 m^2 section covered by the grid, excluding the larger temperature differences of about 2 K generally measured in the corners of the square section.

This distribution is independent of the test temperature and its uniformity does not vary substantially down to T_t = 95 K.

The general configuration of the transverse temperature distribution in the test section measured during the final stabilized phase of cryogenic tests is as follows; a uniform center zone and warmer flow zones near the walls (Fig.18).

The extent of the thermal gradient along the walls, accurately measured by the total temperature probe on one of the walls (Fig.19), covers approximately 50 mm and thus extends considerably beyond the dynamic boundary layer with a physical thickness of 17 mm in the measured section. This extent does not vary with the test temperature from T_t = 200 K to T_t = 105 K.

The amplitude of the wall thermal gradient increases as the test temperature decreases. The total pressure probe readings (Fig.19) appear to show a relatively regular increase in the differences. However, the series of explorations made with the mobile rake show, consistently with the direct wall temperature measurement along the test section, that the maximum difference stabilizes at a value of approximately 12 K for operating temperatures less than or equal to 150 K. The curve of variation of the temperature differences between three points on the cork wall and the flow, illustrated in the Figure 20, concerns a large number of runs down to T_t = 95 K.

The tests do not show a significant variation in the characteristics of the wall thermal gradient when the Mach number in the test section is varied from 0.8 to 0.55.

The practically uniform center zone with a constant width of approximately 300 mm, in which the temperature differences are in the neighborhood of 1 degree, is obtained independently of the cryogenic test temperature. For operation at room temperature, the width of the uniform zone is much larger, approximately 355 mm and the thermal and dynamic boundary layers have the same thickness.

The existence of this center zone, which can be taken advantage of for tests on models over a temperature range of T_t = 100 K in all likelihood, is the important conclusion of this study. The phenomenon of warmer flow zones along the walls is not substantially amplified at low temperature. The origin can be attributed to the addition of heat along the walls of the return line and also to more complex phenomena involved when crossing the stilling chamber.

4.4. Thermal Equilibrium of the CAST 7 profile (C = 150 mm) with the Flow

On the occasion of the first cryogenic tests on profiles, the thermal equilibrium of the CAST 7 profile with a 150 mm chord with the cold flow was systematically checked. The test technique used for this purpose has proven particularly performing for two reasons:

- the satisfactory operation of the model precooling and introduction system; before the run, the profile is cooled to an average equilibrium temperature which is that of a center thermocouple on the upper surface and which is computed from the stagnation temperature of the test taking into account the local Mach number on this point and a recovery factor r by the theoretical formula : $T_{AW} = T_t \left(1 + r\left(\frac{\gamma-1}{2}\right)M^2\right)/\left(1 + \frac{\gamma-1}{2}M^2\right)$. For a turbulent boundary layer, r ~ 0.9 and for a laminar boundary layer, r ≈ 0.85.

- The time, about 30 seconds, between introduction of the profile and the aerodynamic measurements which mainly corresponds to the phase during wich the test section Mach number and the stagnation pressure are increased but also to the initial iterations of the wall adapting process during the stabilized phase. This time is amply sufficient for the flow to complete temperature adjustment of the profile. Actually, an error of a few degrees in selection of the precooling temperature is practically without effect on the final thermal equilibrium.

The figure 21 shows the variation with time of a characteristic temperature on the profile upper surface during the final stabilized phase of the run. The variation, practically null, of the regulated stagnation temperature is also shown as well as that of the theoretical equilibrium temperature T_{AW} for this point of the profile, determined from the stagnation temperature, considering the local Mach number M_l = [illegible]. These tests were conducted with tripped transition in the vicinity of the leading edge at M = 0.76, a stagnation pressure P_t = 1.6 b and an angle of attack α = +0.3°. The tests each included six iterations of the test section wall adapting process and the temperatures were measured each iteration, every seven seconds.

At operating temperatures T_t = 150 K and T_t = 120 K, the profile appears to have practically achieved thermal equilibrium at the beginning of the adapting process, with an accurary better than one degree.

In the figure 22, the temperature distribution measured along the chord on the upper surface of the center section of the profile is compared with the theoretical distribution of the equilibrium temperature calculated from the stagnation temperature and the local Mach number distribution along the chord. This comparison is made for a test with tripped transition and T_t = 120 K. The form of the measured distribution is consistent with the theoretical distribution and the differences are approximately equal to 0.5 K.

These results satisfy a requirement generally retained for thermal equilibrium of a model in wind tunnels:

$(T_{model}/T_{AW} - 1) \leq 1$ percent.

However, this satisfactory thermal equilibrium of the profile is in all likelihood achieved only on a center section 25 cm to 30 cm wide, where the spanwise temperature distribution is uniform (Fig. 24). In the vicinity of the walls, differences of up to 10 K are measured for the test case at T_t = 120 K, due first to conduction heat from the heels which are not directly cooled and which are in contact with uncooled mechanical assemblies. In addition, we know that a zone of warmer fluid exists in the flow near the wall for completely independent reasons and this zone also affects the profile temperature in this region.

Two other interesting points concerning thermal equilibrium of the model can be raised here.

It is known that the equilibrium temperature of a surface with a given flow is not the same for a laminar boundary layer (r = 0.85) as for a turbulent boundary layer (r = 0.9). This phenomenon was observed during tests with free transition at a low Reynolds number (Re_c = 4 10^6; T_t = 250 K) illustrated in the figure 23. In this case, the transition occurs in the location of the shock wave on the upper surface and temperatures corresponding to laminar equilibrium are measured on the model upstream of the shock wave. For the same test conducted with tripped transition, the model is at thermal equilibrium in turbulent state, higher by approximately 3 K. Therefore, to a certain extent, the skin temperature of the model at thermal equilibrium can give additional information on the nature of the boundary layer.

The overall heat exchange between the profile and flow is at the origin of the thermal wake. The transverse total temperature distribution in the wake is a highly significant measure of thermal equilibrium or disequilibrium of the model. For information, the figure 25 shows profiles of total temperatures measured one half chord behind the trailing edge in the following configurations: hot model, cold modeland thermal equilibrium.

Finally, the study of the aerodynamic effect of thermal disequilibrium between the model and the flow, characterized by the parameter T_W/T_{AW}, was also approached with the CAST 7 profile (C = 150 mm). These results are given in the paper mentioned in reference 13, which also covers other, more fundamental aerodynamic problems encountered in the T2 wind tunnel.

5. CONDENSATION AND PARTICLES

5.1. Condensation Phenomena in the Cryogenic Flow- Limit of the Operating Range at Low Temperatures

In the framework of the analysis of the flow qualities, the purpose of this experimental study was to qualitatively detect the presence or appearance of condensed particles in the test section in cryogenic state and clarify the temperature and pressure conditions of the phenomenon.

5.1.1. Optical Detection Device

The detection method is based on the increase in light diffused by a laser beam when the beam is crossed by particles.

The lateral doors of the test section are equipped with two glass windows, facing one another and externally provided with deicing systems. When crossing the test section, the beam of a low power laser cuts through the optical field of a photomultiplier located on the opposite side (Fig. 26). The axes of the laser and photomultiplier are inclined from the normal to the flow to eliminate from the flow field any reflection of the beam on the windows, while keeping visible a center part of the beam crossing the test section.

The laser beam stops on a lateral part of the opposite window, painted dull black. All the tests are conducted with the same geometric adjustment of the device.

5.1.2. Tests and Results

The tests conducted systematically cover the entire operating temperature range down to T_t = 95 K, with a Mach number of 0.8 in the test section and a constant stagnation pressure P_t = 2 bars.

The run conducted at T_t = 95 K (Figure 27), which is the coldest in this series of tests, is a good

illustration of the results obtained.

The consecutive appearance of three types of particles is demonstrated. The particles are identified by the temperature and pressure conditions at the time of their detection.

Ice appears at the beginning of the flow cooling phase at a stagnation temperature of approximately 250 K. The appearance of ice particles is very sudden and they are detected for 10 to 15 seconds, during which their quantity decreases rapidly.

This phenomenon can be explained by rapid crystallization of the water vapor contained in the wind tunnel circuit, after which the dust filter located at the inlet of the chamber captures most of the crystals, producing the decrease in the signal detected by the photomultiplier.

Dry ice then condenses at a stagnation temperature of approximately 135 K. This temperature level is compatible with the partial pressure of carbon dioxide in the wind tunnel, at atmospheric pressure, estimated at approximately 10^{-3} bars. This phenomenon is similar to the above one : rapid appearance and gradual disappearance of the particles trapped by the filter. Finally, an equilibrium is set up between the quantities of water vapor and carbon dioxide injected which constantly produce crystals and the retention operated by the filter. This phenomenon is also indicated by measurement of the pressure loss Δp of the filter which regularly increases during the entire stabilized phase of the run.

Based on the static temperature and pressure conditions in the test section this phenomenon can be attributed to condensation of the stabilized air and nitrogen mixture forming the fluid in the wind tunnel. This phenomenon was fleetingly observed during the test at T_t = 95 K on the occasion of a local drift in temperature. Direct observation by camera allowed us to observe the importance of this condensation and to check that cancellation of the photomultiplier signal (figure 27) was due to a very intense fog.

The instantaneous stagnation temperature measured in the stilling chamber is not a parameter applicable to these condensation phenomena except during the stabilized phase, since during rapid cooling, temperatures which are lower by some ten degrees exist in the circuit upstream of the chamber. Thus, during the test at T_t = 95 K, stagnation temperatures of 270 K and 150 K were measured for appearance of ice and dry ice respectively. Systematic tests conducted at various temperature levels gave further information on the condensation conditions and led to the values given above. In particular, it was verified that for an operating level of T_t = 250 K, practically no particles appeared in the test section and at T_t = 150 K, only ice was detected during cooling. Several tests conducted at T_t = 120 K and T_t = 100 K showed the consecutive appearance and disappearance of ice and dry ice but no substantial passage of particles was detected during the stabilized phase.

The important conclusion of this study is that the fluid condensation phenomenon in the test section is an imperative operating limit at low temperatures. To specify this limit more accurately according to the wind tunnel operating parameters, the dew curve (static pressure and temperature in the test section) of the stabilized mixture 11% O_2 and 89% N_2 forming the fluid in the wind tunnel is expressed as a function of the stagnation temperature, the stagnation pressure and the Mach number in the test section (Figure28). The experimental point (T_t = 93 K,P_t = 2 bars, M = 0.8) is shown on this graph and it appears that a stagnation temperature T_t = 100 K is fully achievable for transonic testing up to a stagnation pressure of 3 bars.

5.2. Problems of Icing and Particle Impacts on the Profile

Two other phenomena were demonstrated during initial testing on the CAST 7 profile, C = 150 mm. After the particle detection tests described above, the alumina pellet drive air drying system was reconsidered and improved. It was checked that it allowed a dew point of approximately -80°C to be achieved. However, the humidity of the air contained in the wind tunnel circuit when idle, which during cryogenic test periods remains closed when no run is in progress, is systematically much higher: the dew point is approximately -30°C. Additional testing made it possible to attribute this phenomenon to retention of moisture by the polyurethane and the other materials used for internal insulation of the circuit. These materials become charged with water when the circuit remains open between consecutive test periods and are then likely to restore the water vapor to the dry air contained in the wind tunnel after a test. These transfers are slow lasting several hours. The internal insulation is a buffer storage of humidity for the wind tunnel which is very difficult to drain and which should moreover be prevented from reabsorbing water.

When the normal test procedure is followed, icing of the profile is prevented: in the precooling box, the profile is in a dry atmosphere, continuously scavenged by nitrogen. When the profile is introduced in the test section, the humidity of the circuit has already been reduced by injection of dry air, in addition, the remaining water vapor condenses as ice crystals a large number of which are stopped by the filter.

However, icing occurs immediately if the cold model (T< 240 K) is introduced in the wind tunnel when off. Air from the wind tunnel not in use must also be prevented from entering the precooling box.

Another troublesome phenomenon for testing is the observation of a non-negligible number of particle impacts on the CAST 7 profile in the region of the leading edge, more particularly in the center of the flow. The ice crystals for cryogenic operation, polyurethane particles from the surface of the insulating foam and dusts of various origins present in the circuit, are responsible, but we are unable to determine the respective share of these agents. This phenomenon is all the more sensitive because the surface hardness of the CAST 7 profile is relatively lower than that of other profiles used in T2 during operation at room temperature.

Before the cryogenic test campaign on the CAST 10 profile, C = 180 mm, complete cleaning of the circuit with refurbishing of the dust filter was conducted, apparently successfully, since practically no further particle impacts on the new profile were detected either for pressurized operation or at low temperature. It thus also seems that the abrasive effect of ice crystals can be considered negligible.

6. TESTING OF THE CAST 7 PROFILE, CHORD = 150 mm AT HIGH REYNOLDS NUMBER

6.1. Model and Instrumentation

The design and construction of this CAST 7 profile model (figure 29), designed for cryogenic testing in T2, resulted from studies conducted by the Direction des Grands Moyens d'Essais of ONERA concerning selection of the material best suited to low temperatures and the assembly minimizing thermomechanical constraints (Ref. 14).

The material selected was a maraging steel, MARVAL 18, with a high nickel content.

The model includes three sections (leading edge, upper surface and trailing edge, lower surface) assembled by welding. The hollow section separating the sections as well as the slots for the pressure tubes and thermocouple wires are lined with nickel felt to ensure uniformity of the thermal mass. One of the ends is used to attach the profile to the translation system in the precooling system and the other to lock the model in place in the test section.

The profile has a chord of 150 mm and is equipped with 103 pressure taps, most of which have diameter of 0.3 mm. In order to solve problems, in particular related to the risk of tripping transition, 32 taps with a smaller diameter (0.1 mm) are provided on the low thickness region of the leading edge boundary layer.

The temperatures are monitored by 18 copper-constantan thermocouples located at a depth of 1 mm under the profile surface (Sec. 4.1.) Ten thermocouples are distributed along the center chord on the upper and lower surface and the others are located spanwise.

The tests included utilization of the self-adapting walls. When adaptation is achieved, three associated probes explore the wake transversely one half chord behind the trailing edge. The two pressure probes, one for total pressure and one for static pressure, have a sufficiently short response time for rapid exploration, over a total time of approximately 10 s. These probes use two miniature Kulite transducers operating at variable temperature, making it possible to reduce the volume between the sensitive membrane and the pressure tap. These probes are supplemented by a total temperature probe (Sec. 4.1.).

Integrating the static pressure distribution on the profile in the adapted test section configuration provides the lift coefficient C_L. The drag coefficient C_D is obtained by integrating the quantity of movement loss of the fluid in the wake.

6.2. General Test Conditions

These tests are conducted with transition tripped by a line of carborundum grains at X/C = 3% from the leading edge. Tests with free transition become impossible as soon as the Reynolds number based on the chord reaches 6 million, when undue tripping of the transition occurs in the region of the leading edge, irregular spanwise up to Reynolds numbers of about 10 million, and due to irregularities in the profile surface. It is probable that the particle impacts described in section 5.2. contributed to reducing the Reynolds number at which this phenomenon occurred.

These tests are conducted at Mach numbers from M = 0.7 to M = 0.78, stagnation pressures of up to P_t = 3 bars and down to a stagnation temperature T_t = 105 K. The Reynolds number based on the chord varies from $Re_c = 3x10^6$ to $Re_c = 20x10^6$. A large number of tests were conducted for this second value of the Reynolds number, corresponding to the configuration (T_t = 110 K; P_t = 2.5 bars); condensation is avoided in the overspeed region (ML 1.2), on the upper surface (Fig.28).

6.3. Main Results

The effect of the Reynolds number on the test case M = 0.76 and α = 0.3 degrees was studied first. This case corresponds to a lift coefficient of approximately 0.5 and it particular gives rise to correlation testing with the same value of the Reynolds number obtained by different combinations of pressure and temperature. The figure 30 shows the local Mach number distributions on the profile for the same Reynolds number, $Re_c = 6x10^6$ obtained at room temperature for a stagnation pressure P_t = 3 bars and at low pressure P_t = 1.6 bars for cryogenic operation at T_t = 190 K. The two distributions are practically the same in spite of the high sensitivity of the CAST 7 profile to the test conditions, in particular concerning the location of the shock wave on the upper surface. The good definition of the test Mach number by the adaptive walls also contributes to this result.

The figure 31 shows the Mach number distributions on the profile and the total pressure distributions in the wake for the case M = 0.76, α = +0.3 degrees for three different values of the Reynolds number. This example is a good illustration of the effect of an increase in this parameter.

- the shock wave on the upper surface in further back, which increases the extent of the overspeed region and creates an increase in the lift
- in the wake, the loss of speed decreases in the pocket corresponding to the junction of the lower surface and upper surface boundary layers, but the loss increases in the region downstream of the shock wave on the upper surface. In general, the first phenomenon predominates for moderate angles of attack and Mach numbers and a decrease in the drag coefficient C_D is obtained when Re_c increases. However, an increase in the C_D can be observed for cases where the intensity of the shock wave increases considerably as Re_c increases, i.e. at high angles of attack or test section Mach numbers.

The increase in the lift coefficient C_L as a function of the Reynolds number, for the case (M = 0.76; α = +0.3) is illustrated in the Figure 32 for interval $3x10^6 < Re_c < 21x10^6$.

Other significant results of this campaign of tests with tripped transition are given in the Figures 33 and 34 :

- polar curves obtained at Reynolds numbers $Re_c = 3x10^6$ and $Re_c = 20x10^6$ for a Mach number in the test section M = 0.76; a sharp increase in L/d with the Reynolds number is observed
- the variation of the drag coefficient C_D for a given angle of attack α = +0.3 as a function of the Mach number for various Reynolds numbers, Re_c = 3,8 and 20 million. The same phenomenon of a sharp increase in drag with the Mach number is observed starting from a value between M = 0.75 and M = 0.76. The phenomenon is amplified at a high Reynolds number since lower drag coefficient values are found for moderate Mach numbers and higher ones for high Mach numbers, of approximately 0.78. It is however difficult to conclude on a significant increase in the drag divergence Mach number with the Reynolds number.

7. CONCLUSIONS AND PROSPECTS

Aerodynamic testing at high Reynolds numbers are, with the wall adapting methods, obviously the main future prospect for the T2 wind tunnel. Improving operation of the facility remain a constant goal.

From the standpoint of the cryogenic test technique, another interesting line of research is now being approached: building of metal models with a relatively thin skin, only a few millimeters thick, which could be cooled by the flow itself. Interest in this idea, which was not retained for the first cryogenic models used in T2, has been revived in the present context: satisfactory operation of the facility as a whole during long runs, of a duration exceeding 100 s, was verified (satisfactory thermal protection of pressurizable steel walls, reliability of the systems). Better experimental data have been obtained on the time required to cool a metal model by the flow and a run starting process can be considered which achieves a good tradeoff between the model cooling speed and liquid nitrogen consumption. Finally, the complexity of the systems required to precool and introduce in the test section models more complex than a straight profile (sweptback profile, half-model with fuselage on the wall, etc.) is a final argument.

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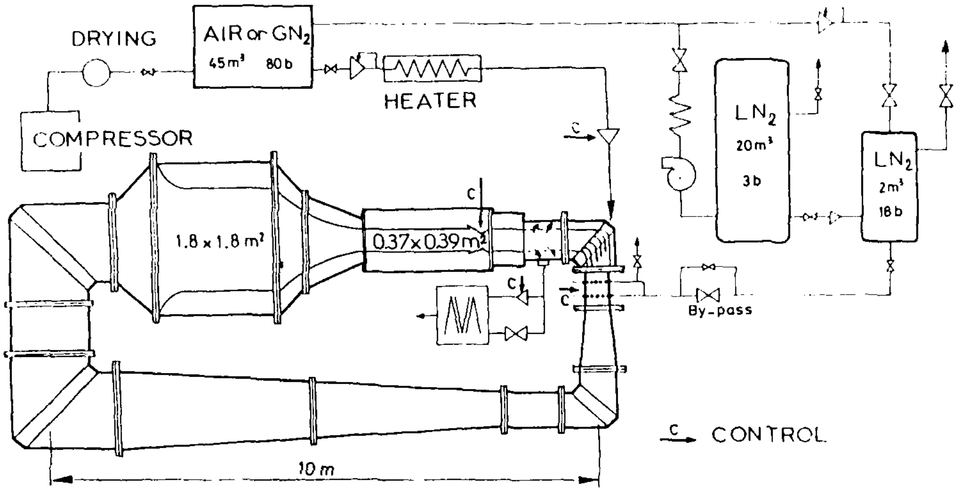


Fig. 1 - Schematic diagram of the wind tunnel T2

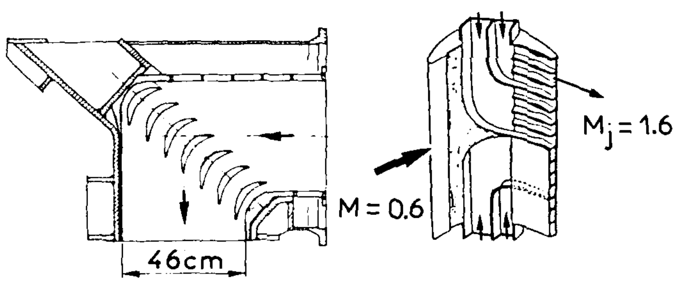


Fig. 2 - Driving air injector corner.

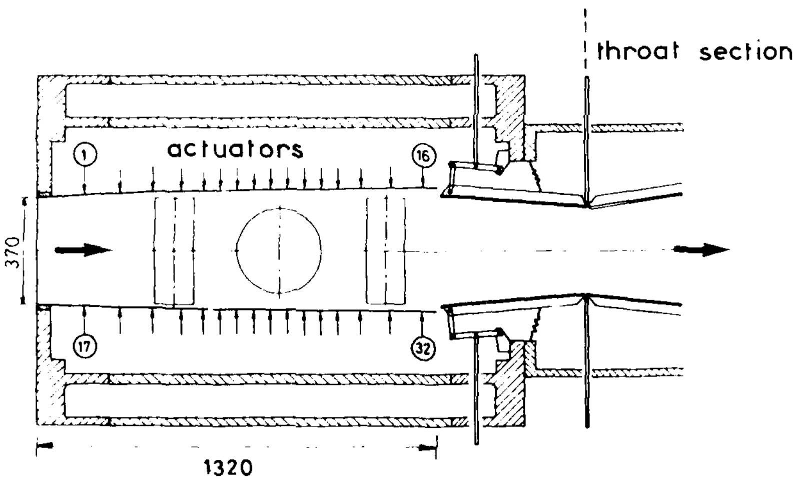


Fig. 7 - Test section and cryogenic self adaptive walls.

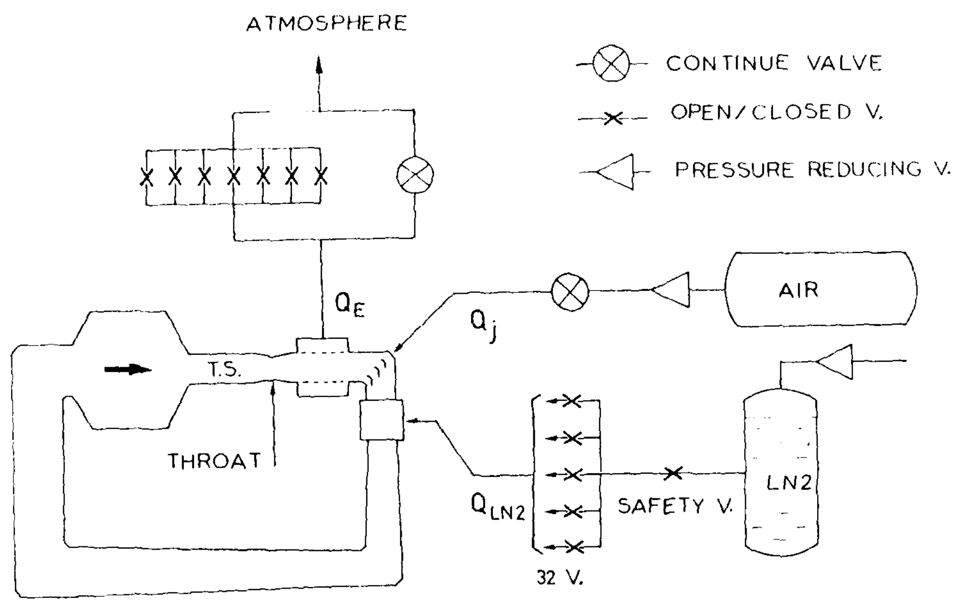


Fig. 3 - Control diagram

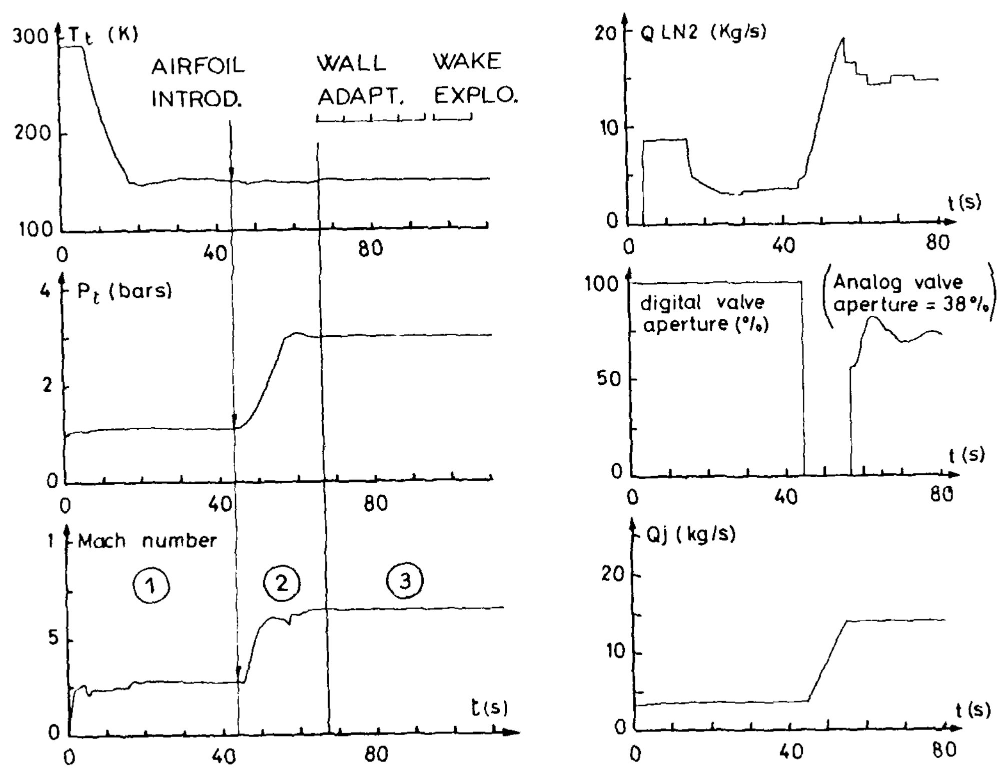


Fig. 4 - Typical cryogenic run : $M = 0.7$, $P_t = 3$ bars, $T_t = 150$ K.

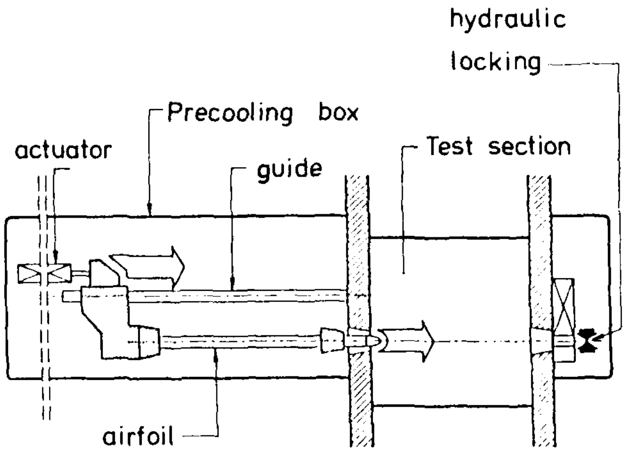


Fig. 5 - Airfoil precooling and translating device.

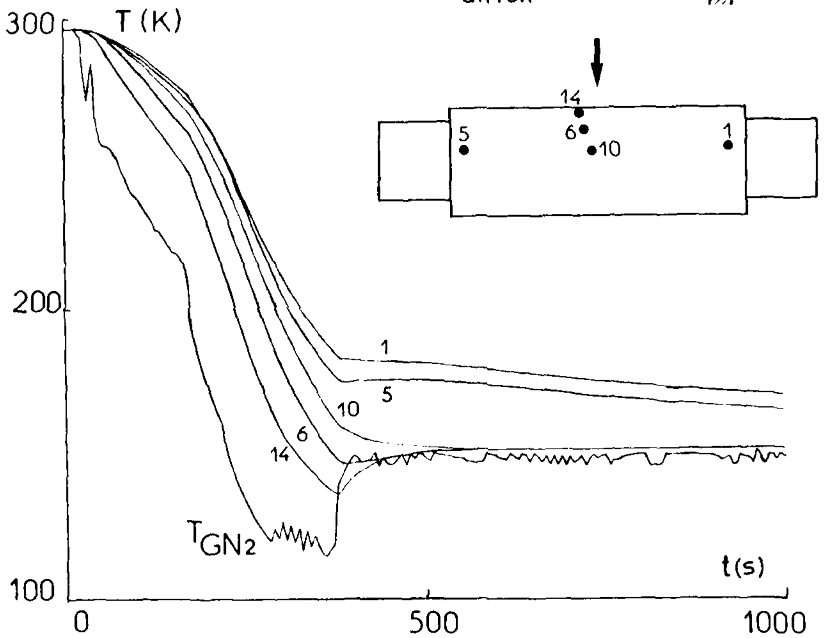


Fig. 6 - Precooling of the CAST 7 (C = 150 mm airfoil.

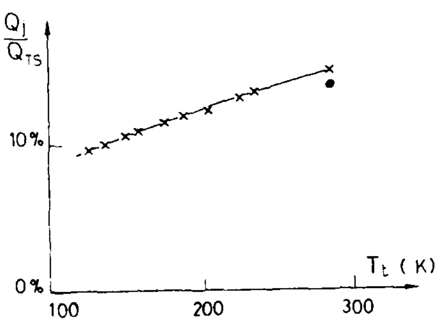


Fig. 8 - Induction efficiency variation with flow temperature.

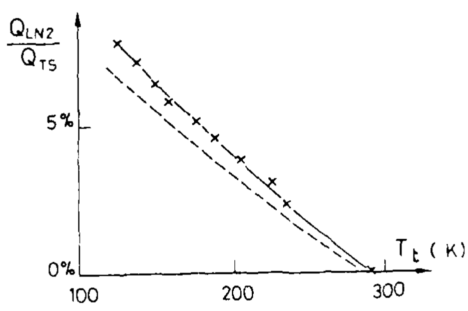


Fig. 9 - Liquid nitrogen consumption

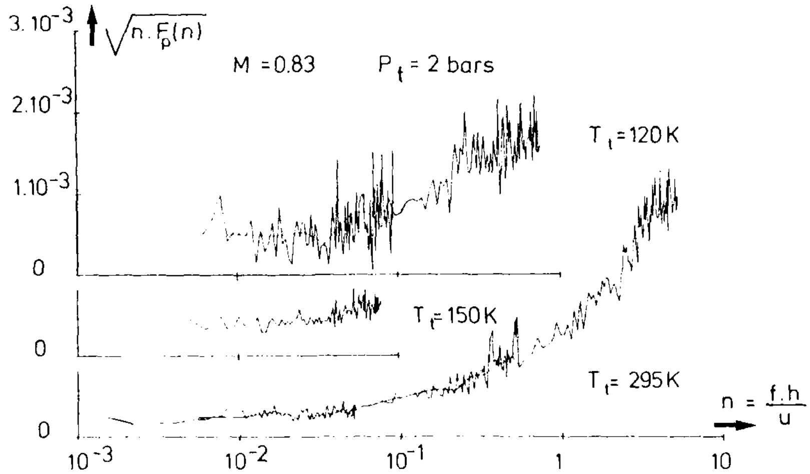


Fig. 11 - Pressure fluctuations spectra.

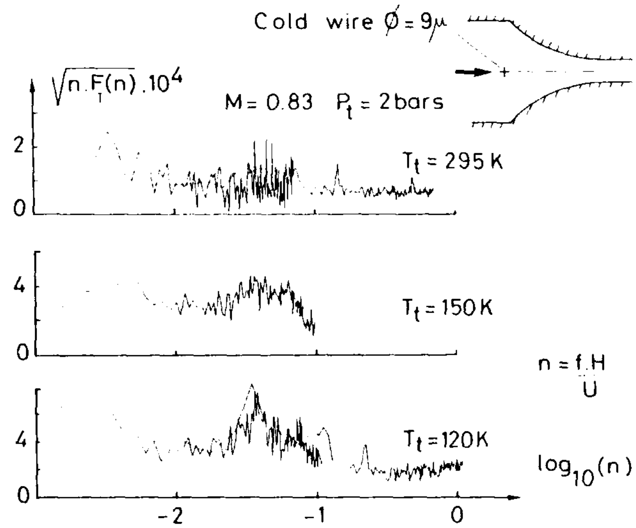


Fig. 12 - Temperature fluctuations spectra.

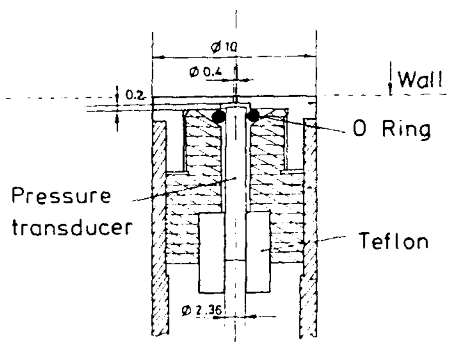


Fig. 10 - Pressure turbulence measurement by a transducer at the test section wall.

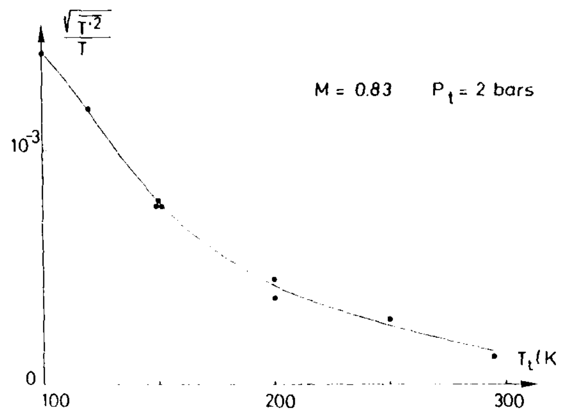


Fig. 13 - Variation of the thermal turbulence level with the flow temperature, for low frequencies ($f < 50$ Hz).

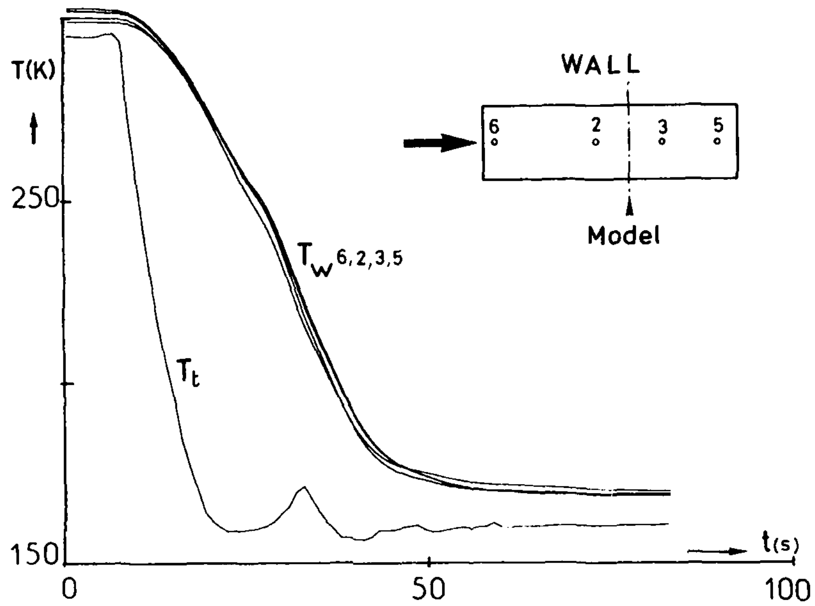


Fig. 17 - Cooling down of the adaptive walls by the cryogenic flow.

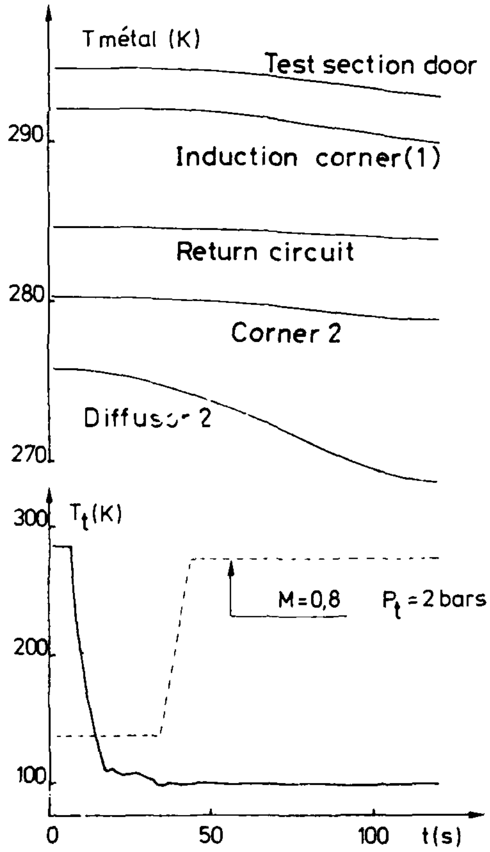


Fig. 16 - Temperature variations of the steel tunnel walls during a run at low temperature T_t = 100 K

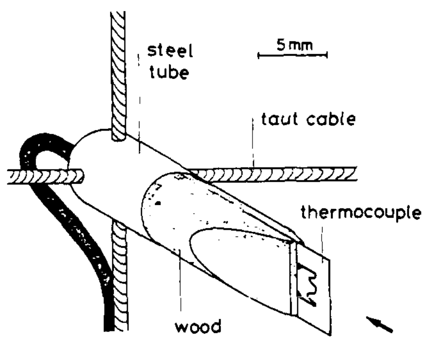


Fig. 14 - Flow temperature probe : here the grid in the stilling chamber.

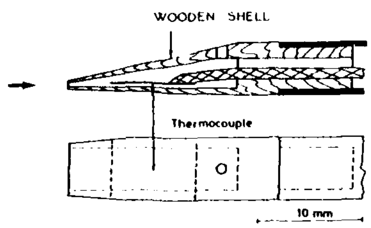


Fig. 15 - Total temperature probe.

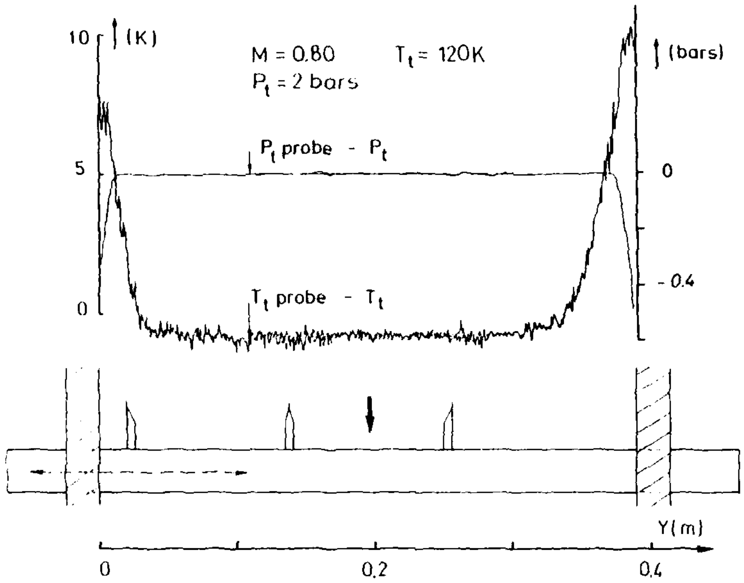


Fig. 18 - Transverse flow temperature distribution in the test section.

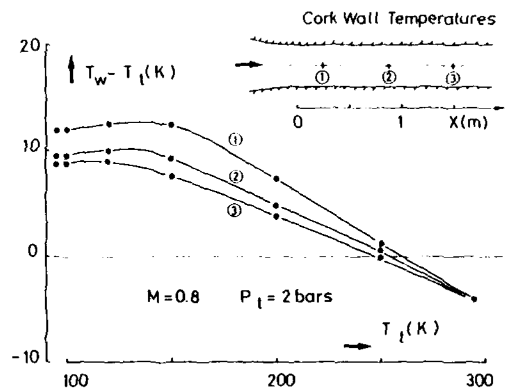
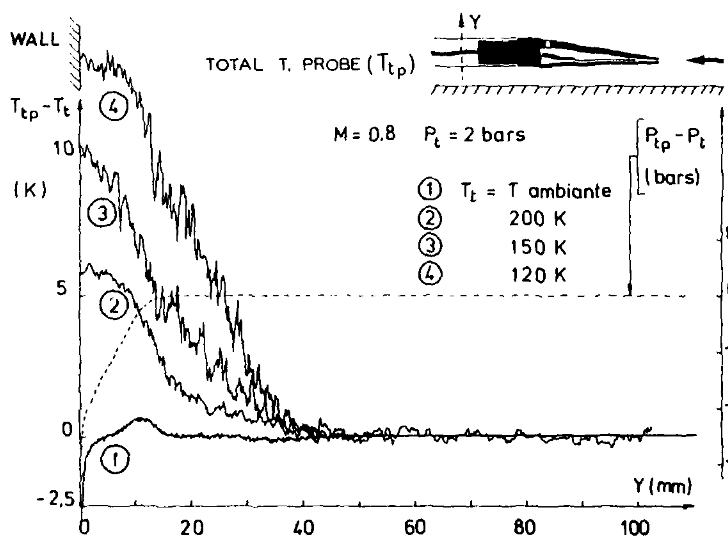


Fig. 20 - Surface temperatures on the insulated walls of the test section.

Fig. 19 - Total temperature explorations near the test section wall.



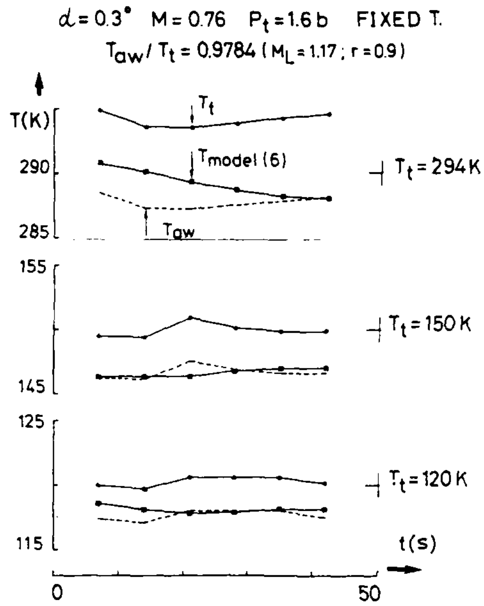


Fig. 21 - Variations with time of the model temperature during the final part of the run.

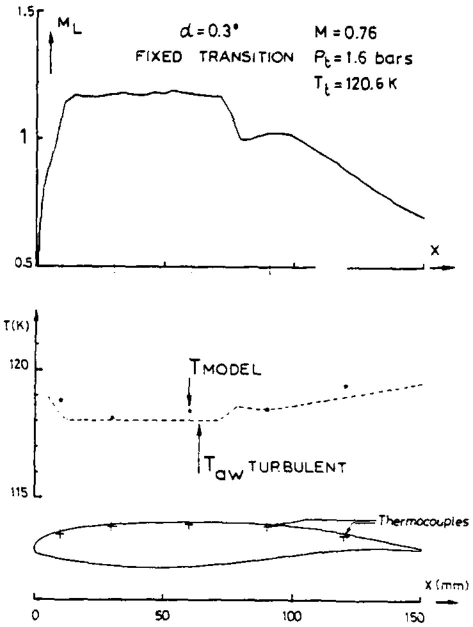


Fig. 22 - Chordwise model temperature distribution, and theoric adiabatic wall temperatures.

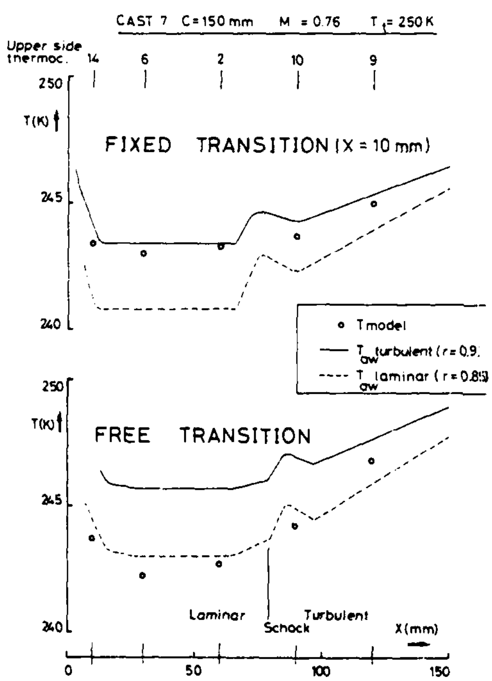


Fig. 23 - Thermal equilibrium of the model in laminar and turbulent conditions.

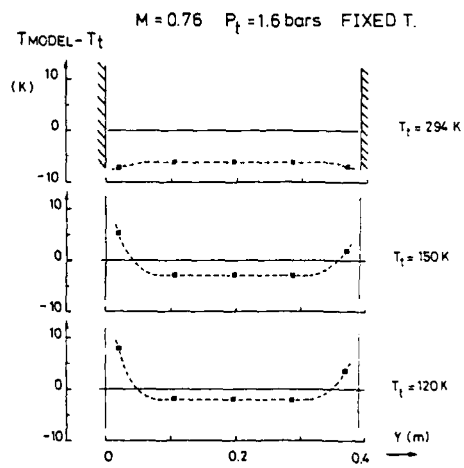


Fig. 24 - Spanwise model temperature distributions.

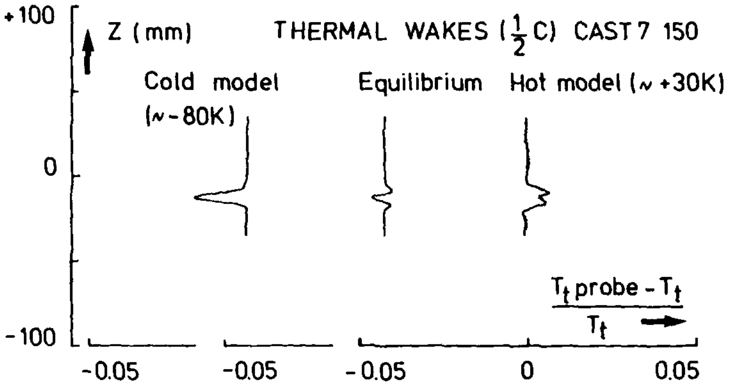


Fig. 25 - Thermal wakes, 1/2 chord behind the trailing edge.

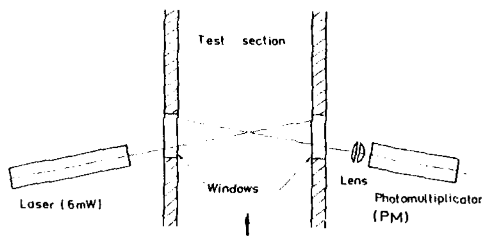


Fig. 26 - Optical device for particle detection.

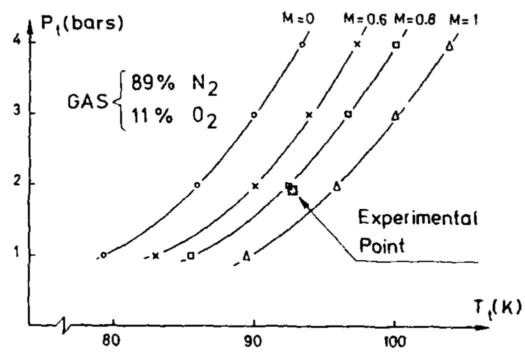


Fig. 28 - Flow condensation limit in the test section.

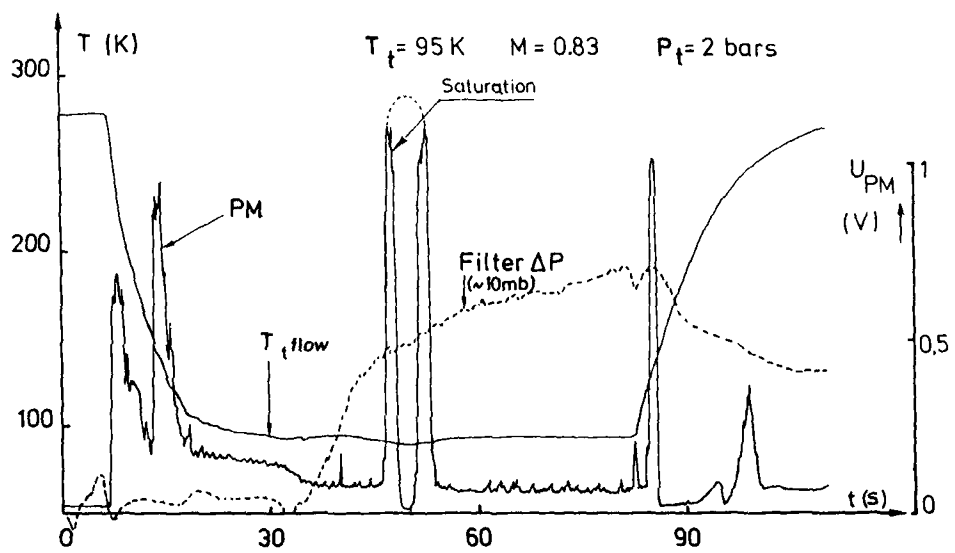


Fig. 27 - Particle detection during a run at very low temperature T_t = 95 K.

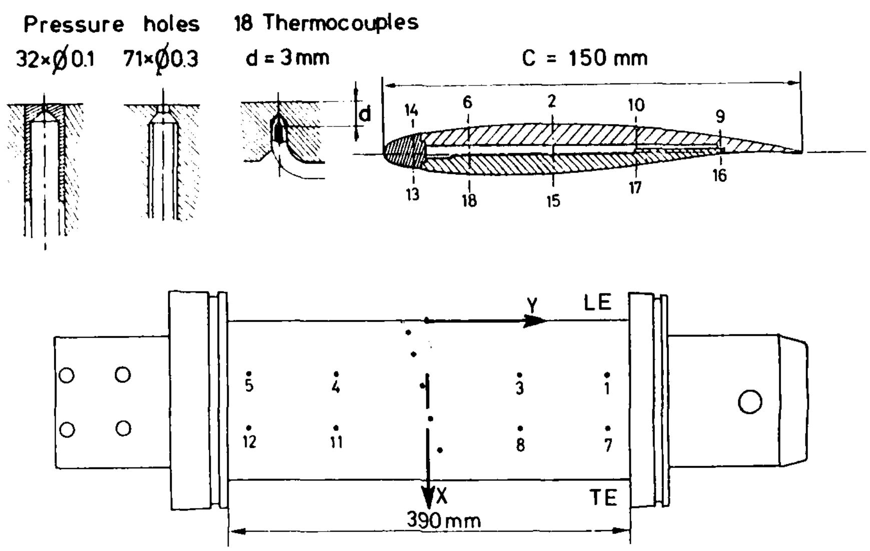


Fig. 29 - The CAST 7 C = 150 mm cryogenic airfoil

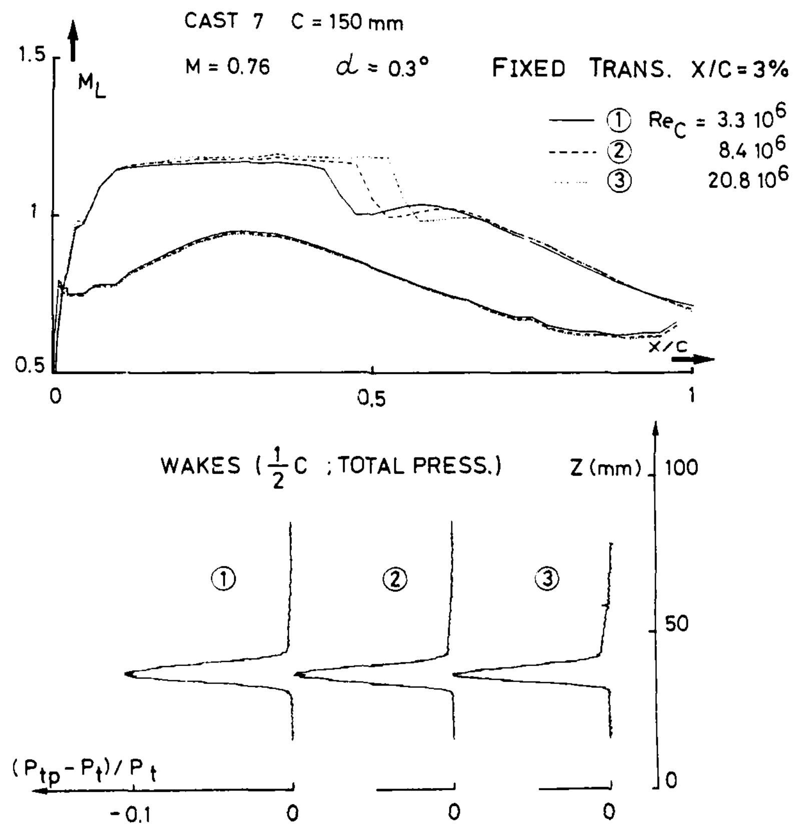


Fig. 31 - Reynolds number effect on the local Mach number distribution and the wake.

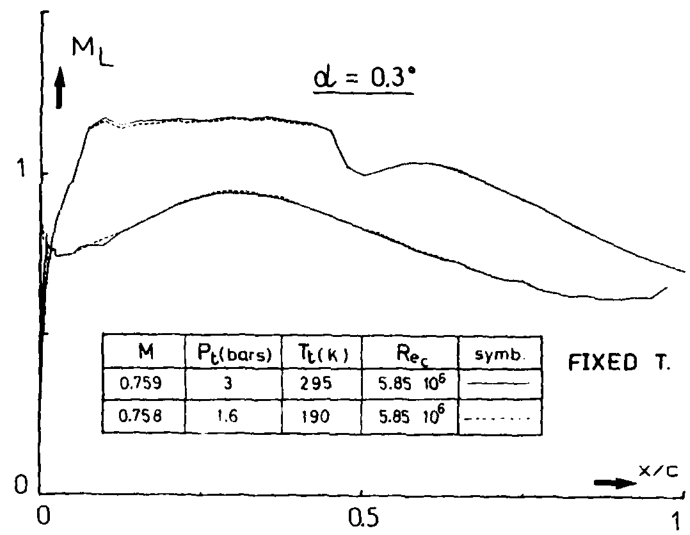


Fig. 30 - Comparison of the Mach number distributions on the airfoil, at the same Reynolds number, for two different pressure-temperature configurations.

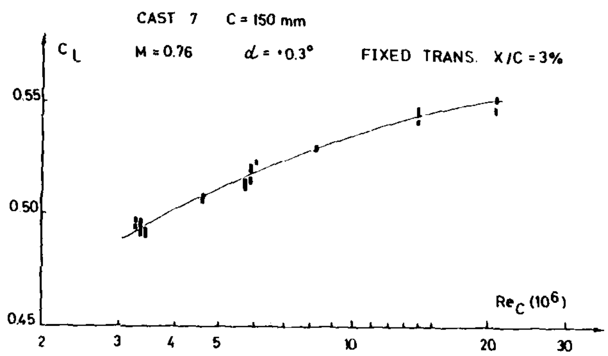


Fig. 32 - Reynolds number effect on the lift coefficient for M = 0.76 and α = + 0.3°

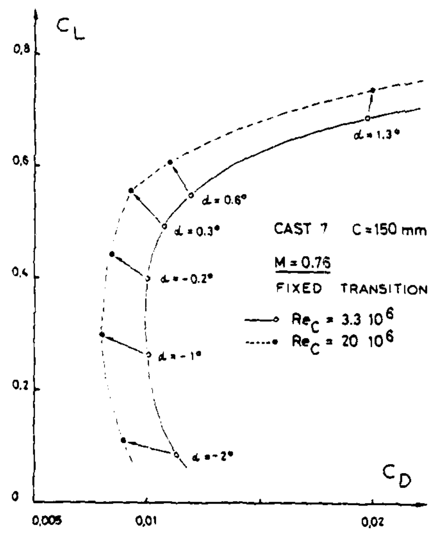


Fig. 33 - Reynolds number effect on the curve lift versus drag for M = 0.75.

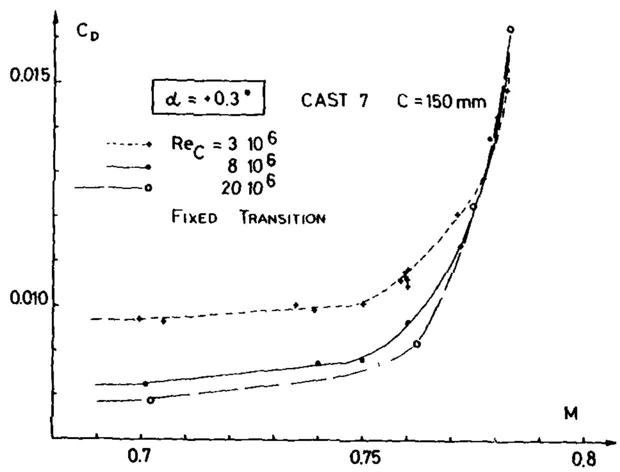


Fig. 34 - Reynolds number effect on the drag rise with the Mach number for α = +0.3°.

THE CRYOGENIC LUDWIEG TUBE TUNNEL AT GÖTTINGEN

by

G. Hefer

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SUMMARY

At the Research Center Göttingen of the DFVLR a cryogenic Ludwieg tube wind tunnel for transonic operation is under construction. The tunnel, having an effective run time of 1 second, a test section of 0.4 x 0.35 m², and a stagnation pressure of 10 bars, is to be operated with nitrogen at temperatures between ambient and 120 K, achieving a Reynolds number of 70 x 10^6 based on a model chord of 0.15 m.

In addition to reviewing the Ludwieg tube concept, this lecture presents the main features of design and operation of the tunnel.

NOTATION

c	Chord of two-dimensional airfoil
L	Length of the charge tube
Ma	Mach number
p	Pressure
Re	Reynolds number
S	Cross-sectional area of the test section
t	Time
T	Temperature
x	Linear dimension

Subscripts

c	Charge conditions
t	Stagnation conditions
ts	Test section
1	Flow conditions in the charge tube

1. INTRODUCTION

The need for high Reynolds number test facilities for the development of future airplanes in Europe led to the decision on the construction of the European Transonic Windtunnel (ETW) which is expected to be operational in 1995. Particularly till that time, but also after the ETW will have started operation, there is a need for high Reynolds number transonic research capability as the ETW will mainly be used for the testing of complete airplane configurations and the use for research purposes will be limited.

A feasibility study, performed at DFVLR in 1982, concerning a research facility suited to investigate transonic flow phenomena at high Reynolds numbers showed that the requirements regarding size, performance and budget limitations could best be met by a Ludwieg tube wind tunnel operated at cryogenic temperatures. A proposal for the design and construction of the tunnel was approved by the Board of Directors of the DFVLR in the autumn of 1982.

2. DESIGN FEATURES

2.1 The cryogenic Ludwieg tube concept

Basically, a Ludwieg tube wind tunnel [1] is a blow down tunnel with a very long storage vessel. Therefore, the discharge process is not a continuous one but takes place in batches with constant flow parameters for each batch. The gasdynamic process is sketched in Fig. 1. The high pressure tube is separated from the low pressure dump tank by a quick opening valve. When the valve is opened, an expansion wave, whose initial spread is given by the opening time of the valve, moves upstream into the tube and accelerates the gas to a Mach number Ma_1 determined by the area ratio of the sonic throat of the valve and the tube, A^*/A_{tube}. The flow parameters behind the wave (region 1 in Fig. 1) are constant as long as viscosity effects can be neglected. The measuring time is determined by the time it takes the wave to travel to the end of the tube and back to the test section. The stagnation conditions (denoted by the subscript t1) are different from the charge conditions (denoted by c). Fig. 2 shows the ratios p_{t1}/p_c, T_{t1}/T_c, the Mach number in the tube, Ma_1, and the length ΔL of the gas column passing through the test section as functions of the Mach number in the test section, Ma_{ts}, for a nozzle contraction ratio A_{tube}/A_{ts} of 3.6 which applies to the tunnel to be described below.

The advantages of a Ludwieg tube wind tunnel are
- simplicity of the system,
- low capital cost,
- high flow quality provided the running time is not too long,
- high discharge efficiency since the stagnation pressure is higher than the pressure of the gas remaining in the tube.

For cryogenic use, additional advantages are
- no temperature distorsions due to LN_2-injection,

- lower stagnation temperature than charge temperature,
- extended measuring time as the expansion wave moves with the reduced speed of sound.

The operating costs are dependent on the nitrogen recovery system; they can be kept low compared to continuous tunnels.

Concerns about the Ludwieg tube tunnel are dealing mainly with the short run time and the impairment of the flow quality due to the boundary layer growth associated with a long run time (long tube) or a small tube to test section area ratio which causes variation of the flow parameters in time and space and increases the turbulence level.

In the present design, this has been obviated by choosing a relatively high contraction ratio and installing a boundary layer bleed system at the nozzle inlet.

2.2 Specifications and general design

The basic requirement for the design of the tunnel was to obtain a Reynolds number of at least 50×10^6 on an airfoil model at transonic speed. For reasons of manufacturing accuracy we have considered a chord of 150 mm necessary with the intention of increasing it to 200 mm when an adaptive wall test section is available. The minimum aspect ratio of an airfoil model being 2 [2], the test section width has been determined to be 400 mm. As the majority of investigations is expected to be carried out on wall mounted models, a relatively high maximum stagnation pressure of 10 bars has been chosen, yielding a Reynolds number of about 70×10^6 at a stagnation temperature of 120 K. In Fig. 3 the Ma, Re-diagram is given for reference lengths of 200 mm, 150 mm and $0.1\sqrt{S} = 37.4$ mm together with the Ma, Re-envelope of the ETW.

Considering flow quality, there is a relationship between run time (i.e. tube length), tube diameter and contraction ratio of the nozzle which determines the discharge Mach number in the tube. In the present case, the basic requirement was a run time of 1 second at cryogenic temperatures resulting in a charge tube length of about 130 m. To keep the maximum discharge Mach number sufficiently low, the contraction ratio has been chosen to be 3.6, yielding a boundary layer displacement thickness of less than 6 % of the radius at moderate stagnation pressures and ambient temperature. At cryogenic temperatures and high pressures the displacement thickness is less than 4 % of the tube radius.

A sketch of the general tunnel arrangement is given in Fig. 4. There are two main shut-off devices, separating the test section from the tube and the dump tank. The main starting device is located downstream of the test section and includes the sonic throat for Mach number control (see 2.3.3). The gate valve upstream of the nozzle separates two charging and temperature conditioning loops: Tube and test section (i.e. model) temperature can be adjusted independently offering the possibility of preconditioning the model to the correct temperature. By this, a putative disadvantage of cryogenic intermittent wind tunnels can be avoided. In addition, the gate valve prevents air from entering the tube when the test section is opened or removed.

Upstream of the gate valve and downstream of the starting device, there are two thrust stands taking the reaction forces. The contraction due to cooling between the stands will be compensated by a bellows upstream of the rear stand; for the same reason the dump tank is seated on sliding supports and the charge tube on rolls.

The entire wind tunnel will be manufactured of stainless steel, German standard X 10 CrNiTi 189 (equivalent to Z6 CNT 18-11 (France), 321 S12 (UK), AISI 321 (USA)), except the nozzle and the part connecting the test section and the quick opening valve which will be made of cast steel.

The external insulation is not yet designed in detail for all parts. The insulating material for the tube is mineral wool covered by a vapor barrier and a layer of glass fiber reinforced epoxy for protection. Every twelve meters, the tube is supported by rings of plywood without any metal connection between the shell and the external support ensuring a uniform temperature along the tube. A nitrogen purge system will maintain the entire insulation at an overpressure of 20 to 50 mbars to preclude entry of air or moisture.

2.3 Description of essential components

2.3.1 Nozzle with gas feeding and boundary layer bleed system

Since in a Ludwieg tube tunnel the gas is accelerated from the state of rest, the initial turbulence level is very low. However, during the measuring period, the boundary layer growing along the charge tube affects both the stagnation conditions and the turbulence level. The first effect can be compensated by a continuous re-adjustment of the control valve. In general, the turbulence level in the test section could be reduced by increasing the contraction ratio (i.e. the tube diameter) or by insertion of a conical diffusor and a settling chamber with screens [3]. These approaches are costly and, in the case of the settling chamber, detrimental to the performance of the tunnel since the starting time would increase reducing the run time. In the present case, a boundary layer bleed system has been designed which is located at the entrance of the nozzle (Fig. 5). A sliding cylinder, moving from the annular space surrounding the nozzle in upstream direction and thereby covering the openings left by the gate and the feeding

ring, opens an annular gap which allows the boundary layer to enter the low pressure annulus. We propose to control the bleed mass flow rate by adjusting the gap width according to the boundary layer displacement thickness.

The fixed contour nozzle is made of austenitic cast steel. The cross section changes from a circle at the lip of the bleeding system to a rectangle of 400 mm by 350 mm at the exit. The design of the bleed system entails a very gradual contraction at the nozzle entrance, thus preventing boundary layer separation in front of the lip.

2.3.2 Test section

A sectional view of the test section is schematically given in Fig. 6. The test section comprises four walls bolted together along the corners. The sidewalls consist of a double-wall structure stiffened by webs and forming a chamber which is to be kept at about the same pressure as the test section before and during a run in order to enable the turn table to be moved and to protect the inner pane of the window. The pressure equalization is to be accomplished by slots or flaps in the rear part of the test section.

The upper and lower walls are single wall structures with external stiffening ribs. The exchangeable slats form a plenum chamber whose volume is about 20 % of the test section volume.

In view of the future usage with flexible walls, the test section has a length of 10 model chords, i.e. 2.0 m, not included the length for the re-entry flaps. These are located in a separate section downstream of the test section which will be used for the installation of a sting support system as well.

The present design of the test section has deliberately been kept simple as it will mainly be used for the verification of the tunnel concept, calibration, and comparative measurements to verify the performance and flow quality of the tunnel. Thus, no sophisticated model support and handling system has been designed. There are turntables in the side walls to mount a two-dimensional model and openings in the upper and lower walls for the installation of movable probes.

2.3.3 Diffusor and main starting device

The crucial components of a Ludwieg tube wind tunnel are the quick-opening valve which starts the flow and the sonic-throat diffusor which controls the Mach number in the test section. Both functions have been combined in the fast-acting control valve sketched in Fig. 7.

The valve consists of an enlarged tube with a centre body which contains two hydraulic actuators used to operate the control cone and the sliding cylinder. The essential requirement placed on the control device is a high accuracy and reproducibility of the cone location in order to accurately adjust the test section Mach number. - The sliding cylinder at the rear of the valve starts the flow by moving downstream. The opening time determines the starting time and, therefore, has to be a small fraction of the run time.

The centerbody is insulated on the inside; the temperature will be controlled by electrical heating.

3. PROPOSED OPERATIONAL PROCEDURE

3.1 Calibration

According to the operational principle of a Ludwieg tube tunnel, the stagnation conditions of the flow can be derived from the charging conditions, if, e.g., the static pressure in the tube is known during the run. Basically, from this set of values the tube Mach number and the test section Mach number can be derived. Thus, importance will be attached to the accurate measurement of the charging pressure and temperature.

For a steady stagnation temperature during the run, the uniformity of the charging temperature along the tube, however, at least over the first third of the tube length, is an important requirement. To accomplish a uniform temperature, a fan circulates the gas through the charge tube back to an LN_2-injection device (see Fig. 4). During calibration, an appropriate procedure of adjusting and equalizing the temperature will be developed by means of detailed temperature measurements inside the tube. After the procedure has been established, the thermocouples will be removed from the interior of the tube and the charging conditions will be measured only at one location upstream of the nozzle entrance.

Calibration of the test section will be performed by pressure measurements along the walls and pitot and static pressure surveys across the test section. Emphasis will be placed on the effect of the boundary layer bleed system and the correct adjustment of the bleed mass flow rate. In addition, tests concerned with the evacuation of the chambers surrounding the test section proper will be carried out. Also planned are measurements to determine pressure fluctuations induced by the various slot and flap arrangements downstream of the test section.

3.2 Test procedure

For a test to be run, the following steps have to be carried out:

- Cooling down and charging of the tube and the test section according to the Reynolds number and Mach number required
- Adjustment of the control valve
- Opening of the gate valve
- Closing of the gaps at the gate valve and the GN_2-injection device by the sliding cylinder
- Starting of the flow by opening of the fast-acting valve
- Closing of the valve after the data have been taken
- Closing of the gate valve after retraction of the sliding cylinder.

The charge time will be about 5 to 10 minutes dependent on the stagnation pressure.

4. STATUS OF THE PROJECT

At the time this lecture is being presented, most of the design work will be completed. The design was performed in-house except for the variable diffusor/quick opening valve whose final design and manufacture is carried out by a contractor. Some of the hardware, like the new building, the supports for the tube, and the dump tank, is erected. The tube will be installed and insulated in spring.

The pressure testing of the tube will be performed in situ with water. All other parts are tested by the manufacturer before delivery. After assembly, a pressure test will be carried out with air. All tests will be supervised by the German Technical Control Board.

The final part to be installed is the diffusor/fast-acting valve, whose delivery is expected in winter 1985-86.

5. PLANS

The first tests and the calibration of the tunnel will be performed in an open circuit, i.e., the test gas will be blown off from the tank during recharging of the tube from the LN_2-storage. After verification of the performance of the tunnel, we plan to close the circuit by installation of a compressor and a heat exchanger to considerably reduce the operating costs (Fig. 8). In addition, we intend to increase the Reynolds number capability of the tunnel by replacing the upper and lower test section walls by adaptive walls. Furthermore, the installation of a more convenient model handling system is considered.

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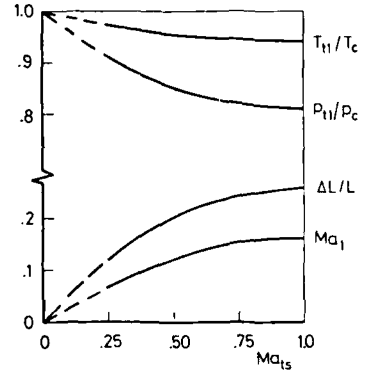

Fig. 2: Characteristic Flow Parameters as Function of the Test Section Mach Number

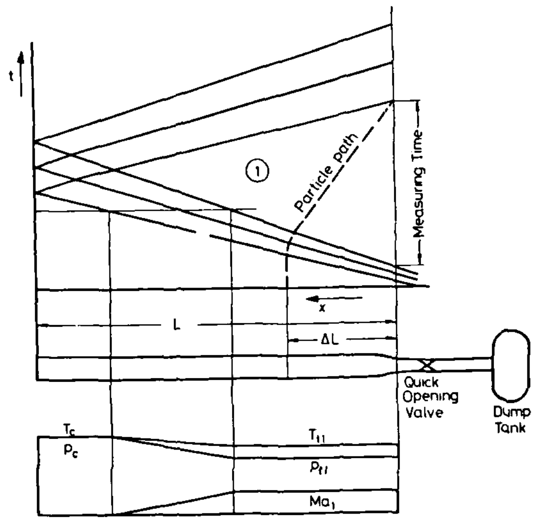

Fig. 1: x,t-Diagram of a Ludwieg Tube Wind Tunnel

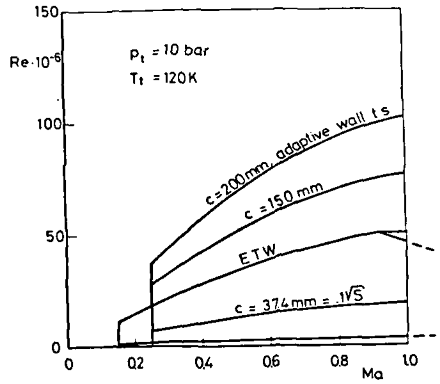

Fig. 3: Re, Ma-Diagram

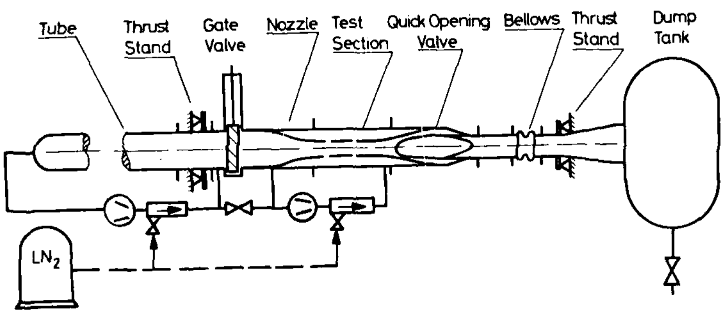

Fig. 4: Cryogenic Transonic Ludwieg Tube, General Arrangement

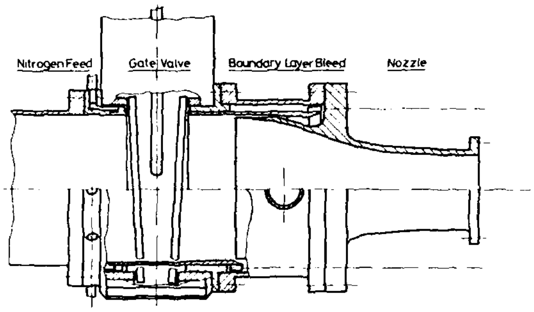

Fig. 5: *Boundary Layer Bleed System*

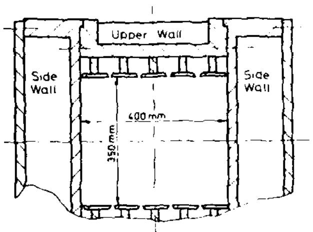

Fig. 6: Sectional View of the Test Section

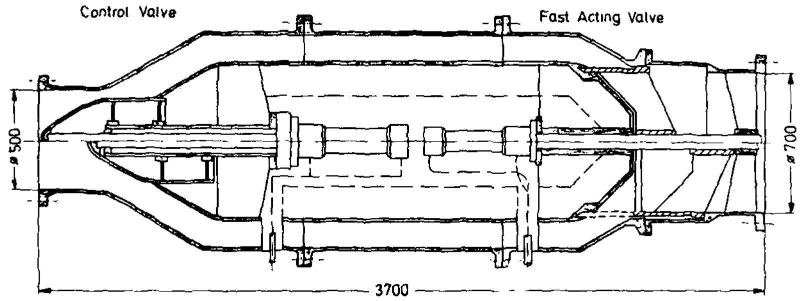

Fig. 7: Diffusor and Fast Acting Valve

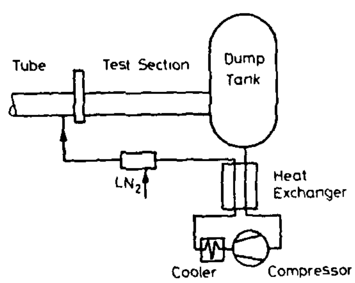

Fig. 8: Closed Circuit with Heat Exchanger

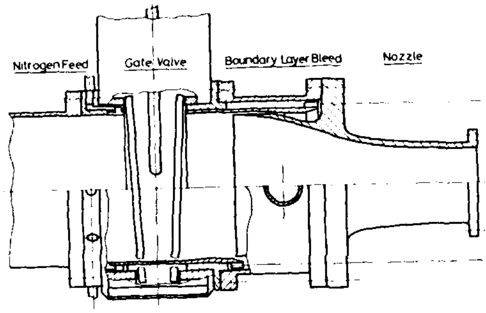

Fig. 5: Boundary Layer Bleed System

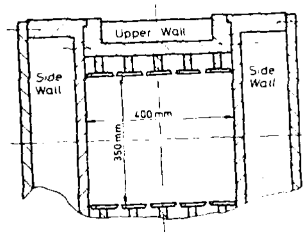

Fig. 6: Sectional View of the Test Section

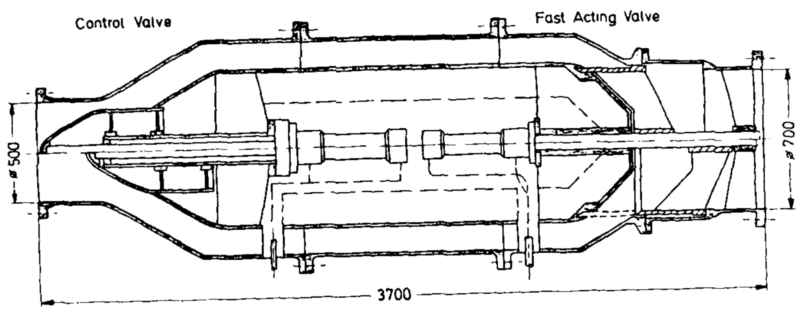

Fig. 7: Diffusor and Fast Acting Valve

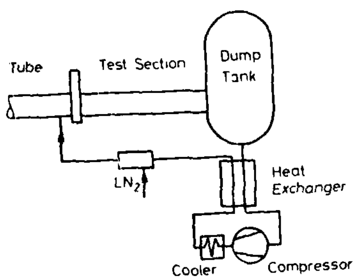

Fig. 8: Closed Circuit with Heat Exchanger

THE KRYO-KANAL-KÖLN PROJECT, KKK

Description of tunnel conversion.
Insulation, controls, instrumentation, operational experience and first preliminary test results.

by

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List of Symbols

A_T	m^2	tunnel surface
A_{TS}	m^2	cross section area of the test section
A_{ME}	m^2	surface of the metal parts
V	m	geometrical factor of the tunnel
u_{TS}	m/s	velocity in the test section
n_F	min^{-1}	revolution per minute
$\dot{m}_{LN_2}$	kg/s	massflux rate of the injected LN_2
$\dot{m}^-_{GN_2}$	kg/s	massflux rate of the exhausted GN_2
$\dot{m}^+_{GN_2}$	kg/s	massflux rate of the injected GN_2
m_G	kg	total gas mass in the tunnel
T_{TS}	K	temperature in the test section
T_G	K	gas temperature
T^*_G	K	temperature of the injected GN_2
T_{ME}	K	temperature of the metal parts
T_W	K	temperature of the wooden cover
T_I	K	temperature in the insulation
T_S	K	temperature of the injected LN_2
ρ_{TS}	kg/m^3	density in the test section
p_{TS}	N/m^2	static pressure in the test section
Δp_F	N/m^2	pressure increase by the fan
t	s	time
τ	s	time delay
i_{LN_2}	[kJ/kg]	enthalpy of the injected LN_2
c_{pG}	[kJ/kg K]	specific heat capacity of the test gas
α_K	$W/m^2 \cdot K$	heat transfer coefficient through the insulation
α_{KM}	$W/m^2 \cdot K$	heat transfer coefficient between the metal parts
η_F	---	efficiency of the fan
K_T	---	loss coefficient of the tunnel
K_{MO}	---	loss coefficient of the test model
Re	---	Reynolds Number
M	---	Mach Number

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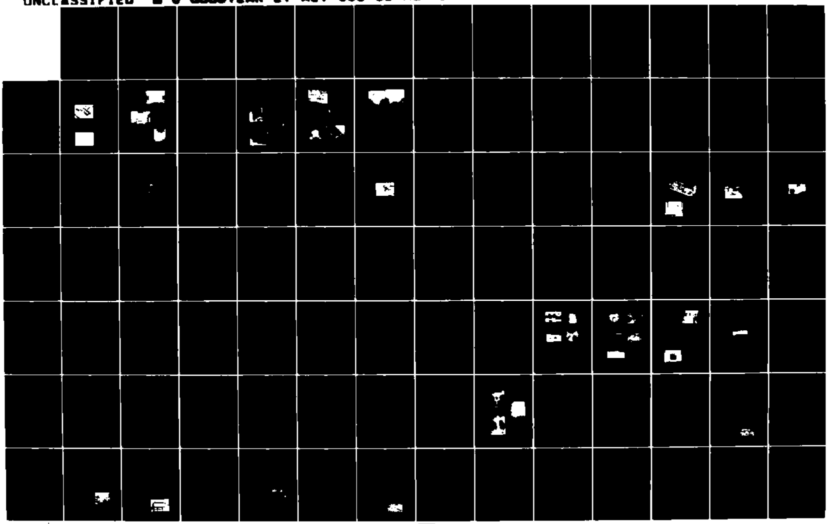

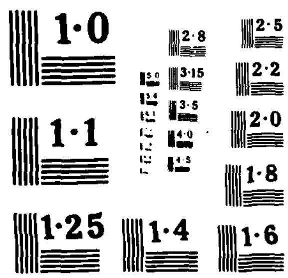
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Summary

The KKK-project aimes at the modification of a low-speed wind tunnel to cryogenic operation. The basis for this decision of the DFVLR consisted in establishing a possibility at a reasonable price for gathering the know-how for the later use of the European Transonic Windtunnel, ETW. The construction is essentially completed and has required a time of about five years. The facility with a test section of 2.4 m x 2.4 m has been designed to operate in a temperature range from 100 K to 300 K. The checkout of all systems will start in April 1985 .

1. Introduction

The way to achieve high Reynolds numbers by using a fluid with extremely low temperatures is followed consequently at the modification of the low-speed wind tunnel of the DFVLR in Cologne [1,2]. According to this principle the 0.3 meter transsonic cryogenic wind tunnel at Langley is operating since 1973; the T2 tunnel of the ONERA in Toulouse and the NTF at Langley since recent time [3, 4, 5].

It is possible to vary the temperature of the test gas in a range between 100 K and 300 K by blowing liquid nitrogen (LN_2) into the circuit. The function between the Re-number and the temperature of the fluid at a constant fan power is

$$Re \sim T^{-1,55}, \quad (1)$$

so the Reynolds number can be increased by a factor of 5.5 by decreasing the flow temperature to a value of 100 K [6]. In the case of the KKK an increase of the Reynolds number above this level by using higher pressures is not possible, because the construction of the shell cannot stand the resulting stress.

Besides the advantage of achieving higher Reynolds numbers at evidently lower drive power than in conventional tunnels a cryogenic wind tunnel offers another one. Beyond the parameters velocity and stagnation pressure which are also operationally variable in conventional wind tunnels, in a cryogenic tunnel in addition the stagnation temperature can be varied. Therefore a separation of the influences of Mach number, Reynolds number and dynamic pressure (deformation) on the test results is possible.

In the final analysis, the additional testing versatility offered by using the temperature as a variable may be as valuable to the researcher as the ability to achieve full-scale values of Reynolds number.

The project KKK is to be seen in connection with the European project ETW. The fact that KKK and ETW have nearly the same test cross-sections, turned out to be an essential advantage. In both tunnels the same models can be tested and there is additionally an overlap in the operation range. During the phases of design, construction and operation of the ETW the scope of the KKK presents the following items:

- support for the national and European programmes of wind tunnel cryo-technology

- development of model- and experimental techniques under cryogenic conditions
- development of an European know-how for the operating of large cryogenic research installations
- functional prove of ETW models
- realization of low cost experiments at lower Reynolds numbers and Mach numbers.

The modified tunnel has the following data:

Test section dimensions	2.4 m x 2.4 m
Model wing span	1.5 m
Static pressure in the test section	atmospheric
Temperature range	100 K to 300 K
Max. Mach number (100 K)	0.38
Max. Reynolds number	8.9×10^6
Fan power	1 MW
Loss coefficient (calculated)	0.22

The Re-Ma number capability of the tunnel is shown in Fig. 1 calculated for a model loss coefficient of $K_{M0} = 0.03$.

Starting in the autumn of 1978 through the year 1979 studies [1, 7] were conducted to develop a modification concept for a cryogenic mode of operation of the 3 m wind tunnel of DFVLR at Cologne [8]. The go-ahead for the project has been decided in May 1980. Design and construction of the facility lasted a period of nearly five years and will be completed in March 1985. First checkouts were performed for the model conditioning room, the liquid nitrogen system and the exhaust system under cryogenic conditions as well as for the fan under ambient conditions. The calibration phase of all components will start in April 1985.

This paper describes the facility components, especially the control system and discuss the status and presents the calibration plans.

2. Description of the Facility

An aerial view of the KKK, as it presents itself today, is shown in Fig. 2. Note the two liquid nitrogen tanks, and the stack of the exhaust system with its location near the second cross leg inside the circuit.

The aerodynamic circuit and other typical features of a cryogenic tunnel are shown in Fig. 3. All components, except the shell, had to be replaced by components with suitable material characteristics. Furthermore, the KKK has some unconventional features, which are necessary for cryogenic wind tunnel testing: a test section including an access lock and a model conditioning room, a liquid nitrogen injection system, a fan driven exhaust system, an internal insulation, and last not least a control system.

2.1 Test section, Access Lock, and Model Conditioning Room

The contraction, with a transition from an octogonal cross-section in the settling chamber to a square cross-section in the test section, has an area ratio of 10.3 to 1 (Fig. 4). The test section, as shown in Fig. 5, is 5.4 m long and 2.4 m square with a cross-section area of 5.76 m^2. The top and the bottom walls are parallel, the side walls are slightly divergent with provision for 4 windows (Fig. 6). In general, models will be sting supported by a circular arc strut permitting a pitch range of 30 degrees with a change rate of 0.2 degrees per second. The model roll angle range is 90 degrees at 0.5 degrees per second. Sideslip angles are obtained by combinations of pitch and roll.

Below the test section the access lock and the model conditioning room are located (Fig. 7).

After a test run the model support is lowered from the tunnel into the lock. Then the lock is separated from the tunnel by a horizontal door, which when the tunnel is running is stored in a parking room. For model changes the interior of the closed lock is warmed up to ambient temperature by blowing in warm gaseous nitrogen (GN_2). A heating system has been installed, which heats and recirculates the GN_2 to the access lock. Before human entry dry air will be blown in. The estimated access time to the lock will take approximately 4 hours, because the great masses of the model support and lifting systems have to be warmed up to ambient temperature.

For minor changes, for example a flap angle change, the model is shifted into the model conditioning room. In this small room the warm up process can be carried out in about 30 minutes time. To use the model conditioning room is considerably cheaper than the lock, because the ratio of the operating costs is 1 to 10. Therefore the effectivity of the KKK is greatly increased. The doors of the lock and the model conditioning room have provision for windows and several smaller ports for lighting and handling of the model.

All movements in the lock and in the model conditioning room are controlled by a microcomputer from the control panel which can be seen in the foreground of Fig. 7.

2.2 Fan and Drive System

The fan has a diameter of 4.3 m (Fig. 8) and is powered by a 1 MW variable speed induction motor. The fan has some specifications, which permit operation at very low temperatures:

- The fan lies on an assembly of prestrained springs, which permit a change of diameter due to temperature change up to 12 mm. These bearings are heated.

- The fan axis is supported only in the cylindrical part of the nacelle, in order to prevent additional tensions due to temperature decrease.

- During cryogenic operation of the wind tunnel, the inside of the nacelle will be ventilated with warm GN_2 to keep the temperature of the bearings, couplings and shaft at approximately 300 K. The pressure of the warm circulating gas is higher than the static wind tunnel pressure to prevent cold gas penetrating from the tunnel into the fan nacelle.

- The main bearing is lubricated with warm oil.

- Important supply and control systems are redundant for safety reasons during operation.

- For material pairings only materials with indentical physical characteristics are used.

A view of the installed fan can be seen in Fig. 9. Note the struts in the foreground, which support the nacelle. The fan has 12 blades and 19 guide-vanes.

2.3 Liquid Nitrogen System

The liquid nitrogen is injected into the gas stream with a system of small nozzles behind the corner vane 2. The station of injection is located more than 80 m upstream of the test section to ensure that the temperature unequalities, originated by the injection, will vanish at the entrance of the test section.

For the specification of the injection system theoretical calculations and experimental tests were carried out. With the aid of an evaporation and mixing model calculation for the interaction between the LN_2 and the gas flow the optimum distribution of the coldsources could be estimated [9]. In the mathematical model the tunnel cross-section at the injection station was divided into finite elements and the positions of the coldsources were varied. Because of the tunnel symmetry it was sufficient to calculate only the mixing in one eigth of the cross-section, the result of which is shown in Fig. 10. The maximum local temperature difference is plotted versus the mixing length for different injection locations. The gas temperature is 100 K, the tunnel has maximum speed (70 m/s in the test section) and the massflux LN_2 is 4.8 kg/s.

The calculations have shown, that the temperature peak decreases rapidly, if one coldsource is surrounded by as many free elements as possible. This is essentially true for the elements 9 and 16. The centerline injection, i.e. element 1, is most disadvantageous.

The results obtained by calculations were checked in a pilot tunnel scaled 1 : 8 to the KKK [10, 11]. The temperature distribution could be measured in 6 cross-sections from the injection station downstream to the test section. The ratio of massfluxes of the streaming gas to the injected LN_2 and the direction of injection was varied.

It could be seen that with the injection in reverse direction to the gas the most intensive mixing and so the most rapid decrease of the temperature peaks took place. But because in this case an exact control of the massflux was only possible at higher regulation pressures, the injection direction was chosen perpendicular to the gas stream, which guarantees a good mixing as well. In Fig. 11 one experimental result of the injection parallel to the gas stream is shown. The ratio of massflux was $\dot{m}_{GN_2}/\dot{m}_{LN_2} \approx 50$ and the velocity in the test section was 20 m/s. It can be seen, that in a distance of one tunneldiameter downstream of the injection station the temperature difference between peak and gas has a value of $\Delta T \approx 50$ K. After a mixing length of 11 tunneldiameters - the location of the test section - the value is $\Delta T \lesssim 1.5$ K. The requirement of LN_2 for a steady state operation is shown in Fig. 12 with the fan power as a parameter. Without taking into account the heat transfer through the insulation, the LN_2-massflow reaches values between 0.1 kg/s and 4.6 kg/s. For tunnel cool-down and run-up the requirement of LN_2 is nearly twice as high.

The LN_2-system is designed for a range of LN_2-massflux between 0.1 kg/s and 10 kg/s [12]. The LN_2-system consists of two tanks, the pump station, and the injection assembly (Fig. 13). The store capacity of both tanks is sufficient to cool down the tunnel to 100 K and to carry out an average experimental operation for some days. In all 3 pumps, which can be driven in a single or a parallel mode, the pressure is increased up to 25 bar. The control of the amount of LN_2 is done with 10 pneumatically driven control valves, which are mounted outside of the tunnel and which are variable in their massfluxes to cover seamlessly the whole range (Fig. 14).

For small massflux rates of LN_2 the injection will be achieved by the help of the pressurized tanks (5 bar), for rates higher than 1 kg/s by using the pumps. By this method strong throttling of the pumps for the case of a low massflux is avoided, by which the LN_2 would be warmed up about 10 K or more.

The operation using the tank pressure in the range of a low massflux has the advantage, that the tunnel can be kept cold economically during stand-by.

For the control of the tunnel the knowledge of the dynamic behaviour of the LN_2-system is necessary. For the corresponding experiments the nozzle rakes were mounted outside the tunnel (Fig. 15). The experiments have shown, that even with rapid , unsteady changes of 20% of the working range of the control valves the respond times to regulate the pressure are only in the order of 1 second.

2.4 Exhaust and Blow-In System

The exhaust system is located in the second cross leg, because there is the highest static pressure of the tunnel and the lowest velocity which allows a rather interference-free blow off (Fig. 16). The tunnel pressure is controlled by a pneumatically operated valve, which is installed in the pipe between tunnel and the stack (20 m high). For low tunnel pressures the gaseous nitrogen will be sucked out by an injector using ambient air, which is induced by a fan [13]. The fan has a maximum

massflux of 10 kg/s of ambient air. Because the regulating valve for the cold GN_2 is designed for the same massflux, a massflux ratio air to GN_2 of 1 : 1 at an operation temperature of 100 K is obtained. In addition there is another opening at the inlet of the stack, through which ambient air can be sucked, to increase the gas temperature and the amount of oxygen [14]. To prevent possible freezing inside the stack, there are provisions to blow in warm nitrogen gas through a slot near the wall, 6 m downstream of the inlet, as can be seen in Fig. 16.

The stack consists of a double tube: the outer tube with a diameter of 0.8 m forms the structure and is manufactured of plain steel. Therein the thin walled inner tube with 0.6 m in diameter, through which the cold gas streams, is suspended. The slot between the tubes is ventilated.

In October 1984 functional tests with the exhaust system with real massfluxes of cold gas and warm ambient air were carried out successfully (Fig. 17). With massfluxes of 10 kg/s and a GN_2-temperature of 100 K the velocity at the stack exit was about 45 m/s, the temperature 220 K and the O_2-concentration 12%. Even at an air humidity of 96% the GN_2-cloud had an expansion of less than 50 m. There was no forming of ice in the stack; the complete installation worked without problems.

Below the before-mentioned pipe, which is part of the exhaust system, there are two more connections to the circuit. One is connected to the relief system and the second one belongs to the gaseous nitrogen injection system. Due to the given pressure limit the priority lies with the relief system (Fig. 18). As already mentioned, the static pressure in the test section has to be the same as the static pressure outside the tunnel, in order to prevent an overload of the concrete shell. Therefore the massflux inside the tunnel has to be increased proportionally to the total pressure during the run-up phase, and warm GN_2 as well as LN_2 have to be injected to keep the test gas temperature constant. The massflux rates of both mediums are controlled by a computer.

2.5 Internal Insulation of the Tunnel

Special care had to be taken in the design of the insulation system, because the tunnel is operating at slightly higher pressures after modification than it was originally designed for. Therefore additional stresses due to temperature differences had to be minimized. It took a three years effort to develop a suitable system, because there was no commercial insulation concept available for a temperature difference of 200 K between both sides of the insulation and a heat transfer rate lower than 15 $W/m^2 \cdot h$.

First a mathematical model of the insulation was developed and the local stresses were calculated for different configurations and materials [15] using the method of finite elements. Because of the high extension coefficients of the insulation materials it was found to be necessary to divide the whole tunnel surface of 2500 m^2 into panels of 1 m x 1 m each. The calculation resulted in a height of the insulation of 0.32 m for the given heat transfer rate. The insulation consists of several layers of materials with different physical characteristics and tasks, because the panels would not only shrink, but there would be serious deformations as well. Fig. 19

compares a panel with and without a temperature difference between the inner and the outer sides. It can be seen, that the panel bulges. The middle section moves into the direction of the warmer part while the edges move towards the region of lower temperatures. Because these movements are not allowed to produce additional tensions in the insulation, the hatched layer in Fig. 19 has to consist of an elastic material. The ideal material for this layer proved to be elastified Polystyrol, which was especially developed for this task. It is unisotropic and permits an elongation up to 80% into one direction, but only up to 5% in the other directions. Elongation and shrinkage in the installed panels are less than 15%. Successful tests were carried out in the cryogenic test assembly of the University of Trondheim in Norway with that configuration, which was found to be the optimum by the calculations performed [16]. The insulation consists of the following components (Fig. 20):

- A vapour barrier, which is glued to the inner surface of the concrete shell.
- A Prepolymer-foam layer with a thickness of 10 cm.
- An elastified Polystyrol foam layer (3 cm).
- Prepolymer-foam blocks of 1 m x 1 m, additionally embraced by an elastified Polystyrol layer.

Wooden covers with the thickness of 18 mm are used as flow liners, they are connected to the shell with rods of low thermal conductivity. Between the wooden covers and the insulation panels there is a hollow space of the same pressure as the static pressure of the flow. This pressure must follow possible sudden pressure changes in the tunnel to prevent excessive bending of the covers. For this reason the covers are perforated [17].

The panels, except the surrounding polystyrol layer, were premanufactured with a high precision. The inside of the concrete shell had to be flattened with an additional cement coating. Then rods werde fixed at regular distances to the inside shell with wall-plugs (Fig. 21). The Figures 22 to 24 demonstrate the different phases of the insulation effort up to completion.

3. Modeling and control of the tunnel

For a cryogenic wind tunnel it is essential, that the tunnel can be operated in an efficient manner in order to minimize liquid nitrogen consumption and the operating costs. The economical and efficient operation of a cryogenic wind tunnel is critically dependent on fast and accurate control of the tunnel variables velocity u_{TS}, static pressure p_{TS} and static temperature T_G. Cryogenic tunnels allow independent control of all the three flow parameters. In order to be able to describe the process in the wind tunnel, several mathematical models were developed:

- single segment model
- linearized model
- multiple segment model.

The single segment model is a further development of the dynamic model, which already has been used for the design of the injection and exhaust systems [18]. The linearized model was used for the layout of the control system and the multiple segment model was used for the testing of the single segment model.

3.1 The single segment model

In the single segment model the variables of state are considered to be concentrated in one, discrete point. In this simplification it is assumed that the internal compensation process is fast with respect to a change of the tunnel variables u_{TS}, p_{TS}, and T_G with time. (An example for the internal compensation process is the temperature distribution along the tunnel axis). The dynamic behaviour of the KKK can be described with the help of the equations of equilibrium, which show the relation between one variable of state and the other variables of state and the input variables.

The variables of state for the KKK are:

- test section gas temperature T_G
- concentrated metal part temperature T_{ME}
- velocity in the test section u_{TS}
- static pressure in the test section p_{TS}
- total mass of the gas in the tunnel m_G

As input variables influencing the process in the wind tunnel are used:

- injected LN_2 massflux rate $\dot{m}_{LN_2}$
- exhausted GN_2 massflux rate $\dot{m}^-_{GN_2}$
- injected GN_2 massflux rate $\dot{m}^+_{GN_2}$
- fan revolutions per minute n_F

Each control input affects all the tunnel variables and the thermofluid dynamical interaction occurs both in the space of the tunnel and in time.

The equations of the mathematical model for the processes in the wind tunnel are derived from the equations of equilibrium.

Equilibrium of heat:

$$
\begin{aligned}
c_{pG} \cdot m_G \cdot \frac{dT_G}{dt} = {} & \alpha_K \cdot A_T \cdot (T_W - T_G) \\
& + 1/2 \cdot (K_T + K_{MO}) \cdot \rho_{TS} \cdot u_{TS}^3 \cdot A_{TS} / \eta_F \\
& + c_{pG} \cdot (T_G^+ - T_G) \cdot \dot{m}^+_{GN_2} \cdot (t - \tau) \\
& - \dot{m}_{LN_2} \cdot (t - \tau) \cdot [i_{LN_2} + c_{pG} \cdot (T_G - T_S)] \\
& - \alpha_{KM} \cdot A_{ME} \cdot (T_G - T_{ME})
\end{aligned}
\qquad (2)
$$

This means, that the change of enthalpy in the tunnel contained gas must be equal to the sum of heat transfer through the insulation, heat of dissipation and the change of enthalpy between the gas and the injected GN_2, minus the enthalpy due to evaporation and minus the enthalpy due to the overheating of the injected LN_2. The sum has also to be reduced by the amount of heat transport between the different metal parts (e.g. fan, corner vanes) and the tunnel gas.

Equilibrium of momentum:

$$
\frac{du_{TS}}{dt} = [\Delta p_F - 1/2 \cdot (K_T + K_{MO}) \cdot \rho_{TS} \cdot u_{TS}^2] / V \cdot \rho_{TS} \qquad (3)
$$

The variation of the momentum of the gas equalizes to the pressure increase by the fan minus the pressure loss in the tunnel and at the model.

Equilibrium of mass:

$$
\frac{dm_G}{dt} = \dot{m}_{LN_2} - \dot{m}^-_{GN_2} + \dot{m}^+_{GN_2} \qquad (4)
$$

The variation of the mass of the enclosed gas is equal to the sum of the injected LN_2 and GN_2 mass, reduced by the sucked GN_2 mass.

In addition to the aforementioned equations there are some sub-models in the mathematical procedure:

- fan-model: the relationship between speed of rotation n_F and Δp_F is described

- wall-model: the temperature *in the wooden cover* T_W and in the insulation T_I is calculated

- Test model drag model: with the angle of attack the loss coefficient K_{M0} is calculated

- time delay model: the transport time delay for an injected LN_2-particle up to the test section is determined.

3.2 The linearized model

For the lay-out of the control system the single segment model was linearized for 7 different operating points (Fig. 25). The common description with time base is chosen for the mathematical description.

$$\dot{x} = A \cdot x(t) + B_0 \cdot u(t) + B_1 \cdot u(t - \tau) + D \cdot d(t) \tag{5}$$

It is	$x(t)$	vector of state
	$u(t)$	input vector
	$u(t - \tau)$	time delayed input vector
	$d(t)$	disturbance parameter (influence of the test model)

The own dynamical behaviour of the system is described by the system *matrix* A. The influence of the input parameters on the parameters of state is described by the matrix B (B_1 for the time delayed dependence and B_0 for the other dependences). D describes the influence of the angle of attack on the vector of state x.

There are great differences between the particular elements of the matrix at the different working points, as the calculations have shown. Some elements change their sign, which indicates the non linearity of the system. The details are described in Ref.[19].

3.3 The multiple segment model

To be able to take into account the temperature distribution along the tunnel axis the equation of heat equilibrium was modified. The number of segments can be chosen freely, because the segments of the mathematical model are independent of the segments of the KKK. Each segment passes the whole tunnel circuit with a velocity not identical with the real local flow velocity.

For each segment the equilibrium of heat is calculated whereas the injection of LN_2 is taken into account only for the segment located at the injection station. The segment being in the test section represents the temperature in the test section. Because there is no heat exchange between the discrete segments the temperature is brought in only by the components of the tunnel.

Test calculations were carried out with the single and multiple segment models [20]. They have shown that the simplification of the single segment model is a good approximation [19]. Furthermore the simulation with the single segment and the linearized model for the earlier mentioned five operating points has shown, that the dynamic behaviour of the tunnel is described with a sufficient accuracy by the linearized model at any given working point.

3.4 The Control System

The control system of the KKK was layed-out according to the linearized model; the concept is provided for a control following the mathematical model of the tunnel behaviour (Fig. 26) and is built up on a modular basis. The tunnel can be operated in a hand mode or in a computer controlled mode, respectively. In the stand-by phases a micro computer unit takes over the control which is at a higher disposal than a normal computer. It also takes over automatically the control of the tunnel if the control computer should fail.

During the stand-by phases the function of optimal values to reach the next working point are calculated by a larger computer [21], and these values obtained are given to the control computer which then controls the tunnel.

4. Schedule

The aerodynamic calibration of the tunnel under ambient conditions will begin in April 1985. The following tests are to be conducted:

- determination of the flow quality in the test section
- determination of the loss coefficients of the different tunnel sections
- check-out of the control systems, especially the trajectories of the fan model

It is planed, to cool down the tunnel in the last quarter of 1985. The calibration for the cryogenic mode of operation is expected to cover a time of more than half a year.

5. Conclusion

The modification of the 3 meter - tunnel of DFVLR at Cologne was completed in March 1985. By cooling the flow temperature to a value of 100 K the Reynolds number can be increased up to 8.9×10^6. The check-out of some systems is essentially completed. The aerodynamic calibration under ambient conditions will begin in April 1985, the cryogenic operation phase is planed to begin in the last quarter of 1985.

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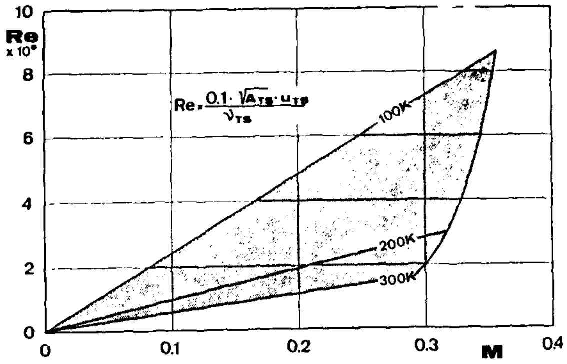

Fig. 1 The Reynolds-Mach Number capability of KKK

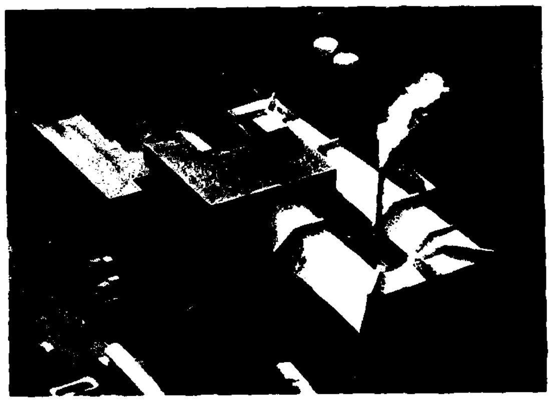

Fig. 2 Photograph of the KKK facility

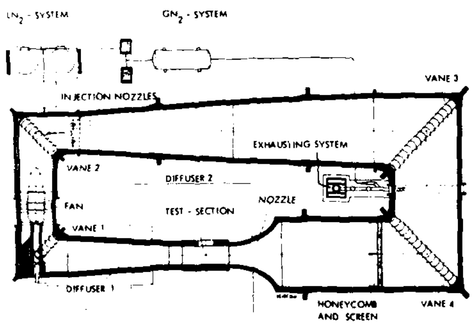

Fig. 3 Plan view of KKK tunnel circuit showing components and arangements

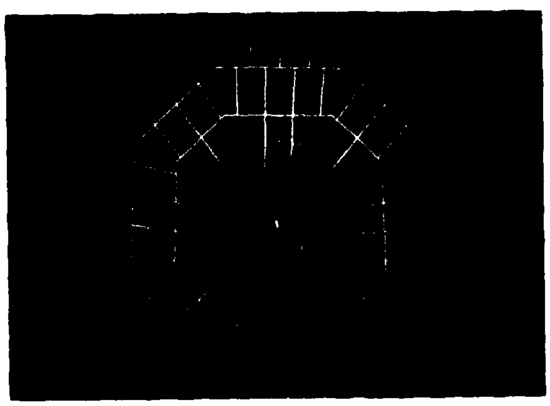

Fig. 4 View of contraction from the settling chamber

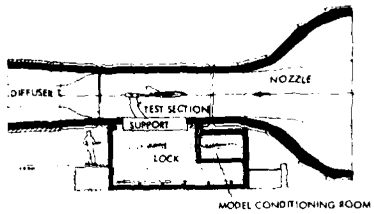

Fig. 5 Test section including Access Lock and Model Conditioning Room

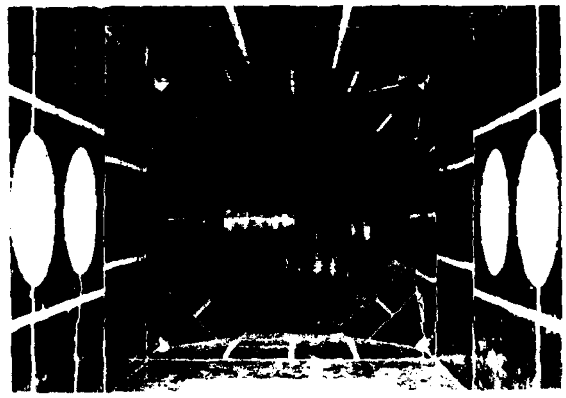

Fig. 6 View of Test section looking downstream

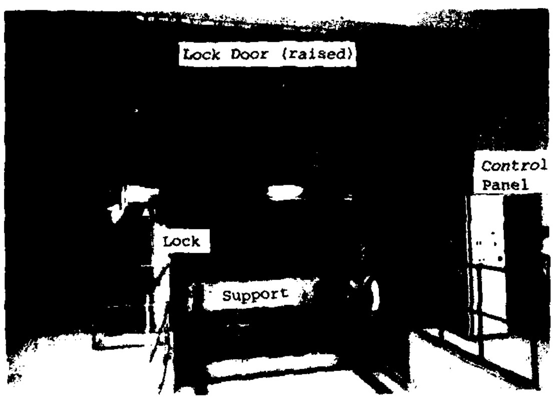

Fig. 7 Access Lock and Model Conditioning Room installed. Shown in the opened condition

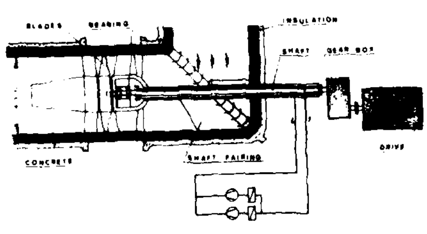

Fig. 8 Schematic view of Fan and Heating System

Fig. 9 View of the Fan

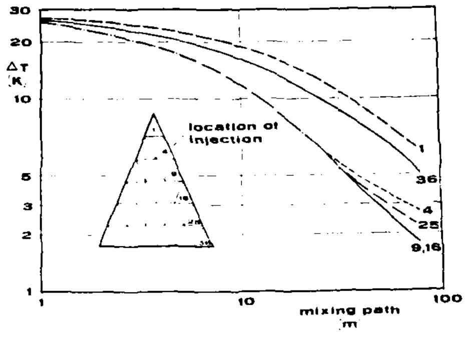

Fig. 10 Propagation of temperature peak downstream of the injection station

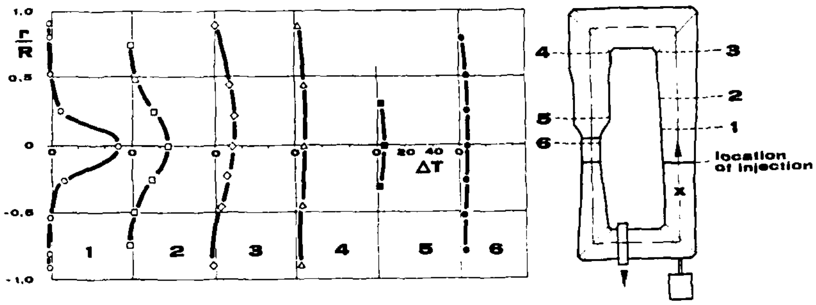

Fig. 11 Propagation of temperature peak for injection parallel to the gas stream in the pilot tunnel. $u_{TS} = 20$ m/s, $\dot{m}_{LN_2} = 0.05$ kg/s

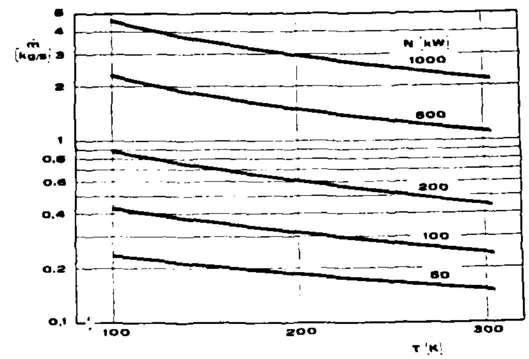

Fig. 12 Consumption of liquid nitrogen in dependence on fan power and test gas temperature

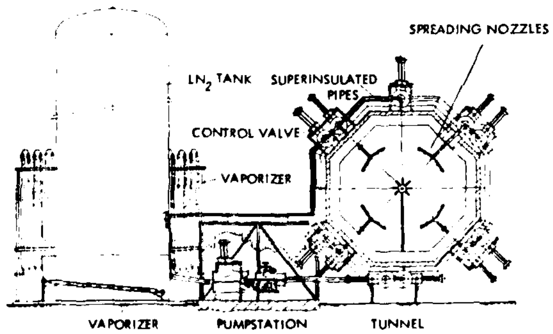

Fig. 13 Plan view of the LN_2-System

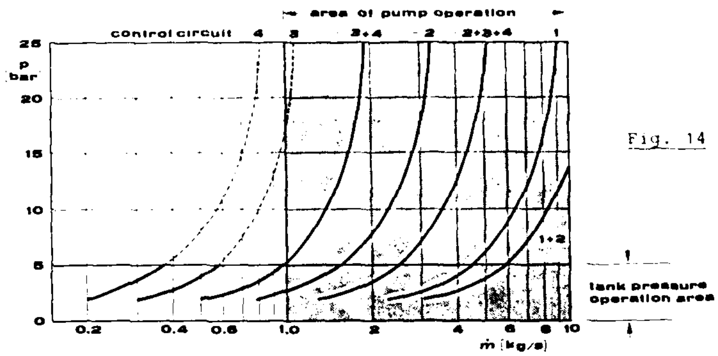

Fig. 14 Mass flow of the LN_2-System for operation by tank pressure and by pumps

Fig. 15 View of the nozzle rakes *located* outside the tunnel during the dynamic tests of the injection system

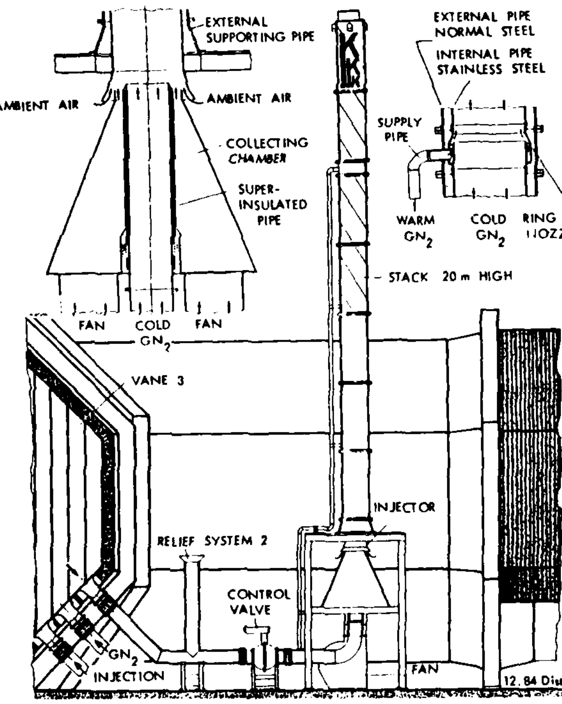

Fig. 16 The Exhaust system with control valve, injector and stack

Fig. 17 View of KKK vent plume taken during checkout

$\dot{m}_G = 10$ kg/s, $T_G = 100$ K

$T_A = 278$ K

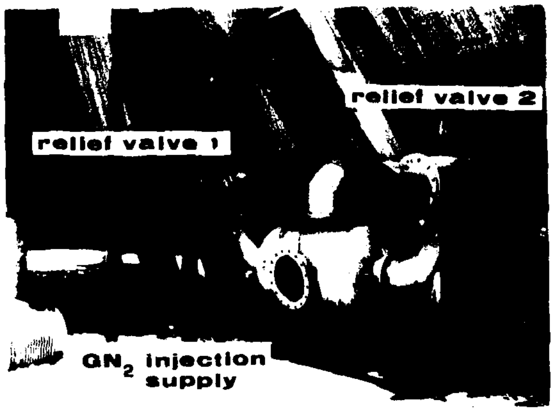

Fig. 18 View of the relief valves and the GN_2-injection system

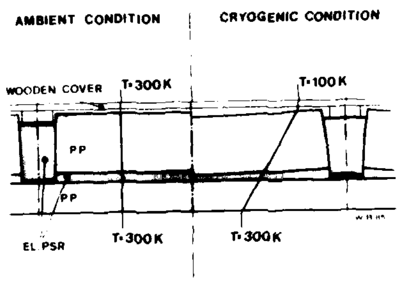

Fig. 19 *Schematic view of an insulation panel for ambient and for cryogenic temperature conditions*

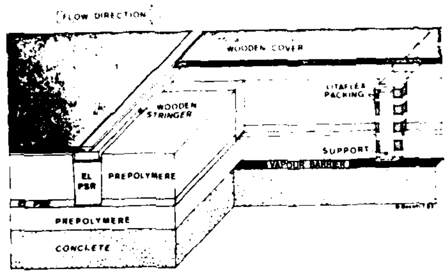

Fig. 20 Schema of the internal insulation system

Fig. 21 Photograph of diffusor 1 with the installed rods of the wooden cover

Fig. 22 Photograph of the next phase of the insulation effort

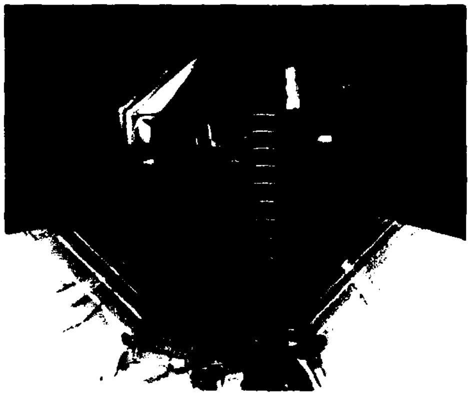

Fig. 23 Installation of the wooden cover

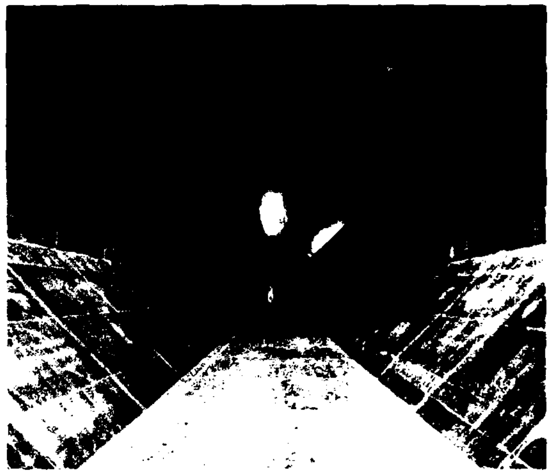

Fig. 24 Photograph of diffusor 2 with the completed insulation

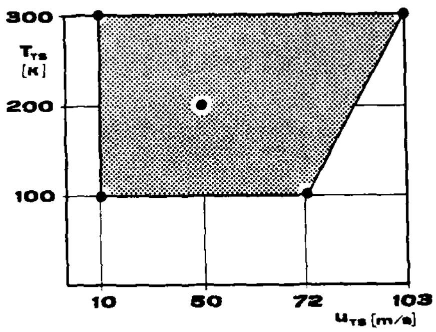

Fig. 25 The five operating points of the KKK for the lay-out of the control system

1: T_{TS} = 300 K u_{TS} = 103 m/s

2: T_{TS} = 300 K u_{TS} = 10 m/s

3: T_{TS} = 200 K u_{TS} = 50 m/s

4: T_{TS} = 100 K u_{TS} = 72 m/s

5: T_{TS} = 100 K u_{TS} = 10 m/s

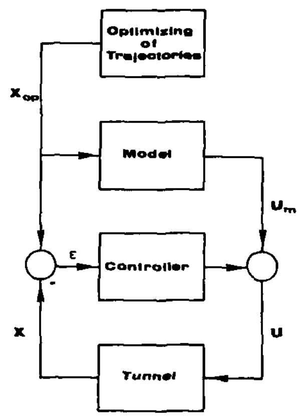

Fig. 26 Control schema

THE EUROPEAN TRANSONIC
WINDTUNNEL PROJECT ETW

by

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SUMMARY

A general description of the European Transonic Windtunnel, ETW is presented with particular reference to:

- the tunnel specification and predicted performance
- the design features related to operation at cryogenic temperatures, including the insulation concept, model access and handling
- a summary of a study on the expected use of the facility
- the flow quality requirements for ETW, including experimental results from an aerodynamic test rig
- the requirement for a second throat and its conceptual design
- a brief description of the pilot ETW (PETW) which is installed at NLR, Amsterdam

Finally a status report of the project and its anticipated future development is given.

1. INTRODUCTION

The Governments of France, the Federal Republic of Germany, the Netherlands and the United Kingdom are co-operating under a Memorandum of Understanding to build a transonic windtunnel for high Reynolds numbers.

The MoU covers the Preliminary Design of the European Transonic Windtunnel ETW. The windtunnel will be of the cryogenic type. Also included in the MoU is the construction of a scale model of the tunnel, the Pilot ETW (PETW). In parallel a programme is performed on model design and instrumentation under cryogenic conditions, in close co-operation with the national programmes of the participating countries.

The Steering Committee ETW, consisting of members named by the respective Governments, has established an international Technical Group. This Technical Group is situated at NLR, Amsterdam until the site of ETW has been chosen. The Group directs the contracts for Preliminary Design ETW, the design and construction of PETW as well as other contracts (special studies, model design, etc.). The Preliminary Design of ETW has been finished and the construction of PETW is completed.

This lecture will present a brief history of the project and the specification and performance of ETW. The expected mode of operation of the facility will be described and the design features, peculiar to this windtunnel, will be summarized. A short description will be given of PETW and of a test rig for aerodynamic measurements.

Finally, the siting of ETW and the time schedule until operation will be addressed.

2. PROJECT HISTORY

The need for new windtunnels for testing at high Reynolds numbers was indicated after an AGARD Fluid Dynamics Panel Specialists' Meeting in 1968. Further developments[1] are indicated in figure 1. It illustrates the important role AGARD played in organizing specialists' meetings and setting up international working groups. The LaWs working group, under the chairmanship of D. Küchemann, recommended[2,3] by the end of 1974 on the basis of: the work done by the Group;, the engineering studies performed and the work done in the participating countries, that a large transonic tunnel should be built according to the specifications given in figure 2. Several drive systems were proposed at the time. (Figs. 3,4 and 5). It was recommended to set up a Technical Project Group for an independent assessment of the available information. This was done under the aegis of the Defence Research Group of NATO (Project Group AC/243 (PG 7)). During the period of this Project Group (1975-1977), the concept of a fan driven continuous windtunnel at cryogenic temperatures was added to the proposed drive system options.

This concept has been developed at the NASA Langley Research Center. The advantages of operating at cryogenic temperatures are illustrated in figure 6. The impact of a reduction of temperature, in this case by injection of liquid nitrogen, on required tunnel power and on Reynolds number are evident. For the same size of model and at the same stagnation pressure the Reynolds number can be increased by a factor of about 6 when lowering the temperature from ambient to 100 K.

Application of the cryogenic concept made it possible to build a smaller facility, operating at lower pressures to obtain the Reynolds number specification of the LaWs Group.

A comparison between the capital costs for earlier drive system options and those for a cryogenic facility with test section dimensions of 1.95 x 1.65 m^2 are given in figure 7.

By the end of 1976 it was recommended to build a continuous fan driven cryogenic windtunnel with the above mentioned test-section dimensions, and this recommendation was accepted.

Early 1978 an international full-time Technical Group which worked under a Memorandum of Understanding between France, Germany, the Netherlands and the United Kingdom, was established at NLR, Amsterdam. The main objectives of this MoU were to perform the Preliminary Design of ETW and to build a pilot facility (PETW).

After the preliminary design was finished the test-section dimensions of ETW were enlarged, with strong support of the European aircraft industry, to 2.4 m x 2.0 m.

Other changes which have taken place since the period of preliminary design include a new concept for model access and the addition of a second throat.

3. ETW SPECIFICATION AND PERFORMANCE

The specification of ETW is presented in figure 8.

The ETW will be a closed-circuit cryogenic transonic windtunnel with a continuous drive. High Reynolds numbers will be attained by injecting liquid nitrogen to decrease the working temperature.

The operating envelope at design Mach number M = 0.9 is presented in figure 9. Although the facility itself is designed for temperatures down to 90 K, a conservative assumption has been made until now concerning the maximum attainable Reynolds number: a minimum total temperature corresponding to flow saturation at a local Mach number of 1.7 has been adopted.

Future evidence might show that this restriction can be relaxed. Figure 10 illustrates that by a drop in total temperature from 121 K at 4.5 bar a substantial increase in Reynolds number is possible. The rate of change of Reynolds number with temperature approaches 1.5 percent per Kelvin at these lower temperatures.

Figure 10 presents the Reynolds number versus Mach number performance of ETW, again with the conservative assumption of flow saturation at local Mach number M = 1.7.
A comparison with the performance envelope of existing European facilities is made in the same figure.

Also the Reynolds numbers of several European aircraft projects in cruise conditions have been plotted in the same figure.

4. PREDICTED USE AND MODE OF OPERATION

Prospective users of ETW were invited to answer a questionnaire and to imagine what types of test they would need in about 15 years from now. In making their replies they were asked to take account of practical constraints on models and tunnel and also of tunnel power consumption and occupancy. They were also asked to indicate the types of test trajectories which would be used, the Mach number coverage, and the pressures and temperatures of the tests. These data were to provide the basis of estimates of the test spectrum and utilisation pattern.

The replies showed that there is considerable interest in the ETW and that many organisations expect to use it for a wide range of model tests.

The analysis of the replies shows that, for the majority of tests, the tunnel would be run at high Reynolds numbers, using the lowest temperature allowed by consideration of condensation phenomena, Fig. 11. However, a number of potential users expected to test over a range of Reynolds numbers, and to avoid model deformation effects, the change in Reynolds number would be achieved by variation of temperature. In these cases the temperature changes needed may be too large to be made during a single tunnel run. The temperature changes during a run will be limited by model temperature lag and possibly by tunnel structure thermal fatigue considerations. Consequently the test requirements were written with the assumption that substantial temperature changes (40 K or more) would be made between tunnel runs.

The relative demand for different types of tests is indicated by the distribution of temperature trajectories, which was obtained by further analysis:

Test Trajectory	% of tunnel testing time
Ambient temperature (· 270 K)	6.5
Constant low temperature (· 150 K)	70
Constant intermediate temperature	14.5
Variable temperature during a run	9

There was substantial customer interest in rapid changes of pressure during a test programme so that consecutive tunnel runs could be made at different pressures and constant temperature (or with small variations in temperature). Also a rapid decrease in

pressure during a run may be needed for tests at high pressure which extend to Mach numbers above 0.9, in order to stay within tunnel power limits.

The distributions of testing time for each pressure and Mach number range are also shown in figure 11.

The distribution of tunnel testing time between the different types of test (Fig. 12) is close to that for existing tunnels. It shows a slight increase in the amount of unsteady testing when compared with figures obtained previously as would be expected.

Prospective users of ETW were also asked to imagine what test techniques they would need in the tunnel.

The replies indicate that most customers envisage high levels of test technology to be available for use. The demands for model deformation measurement and engine-flow simulation are understandable, so that the improved simulation accuracy coming from high-Reynolds-number testing should be matched by improved accuracy in other directions. Nevertheless, the provision of many of these facilities (Fig. 13) for routine use in ETW will be challenging and they will need to be worked on in parallel with tunnel design and construction.

It is inevitable that further changes in testing patterns will take place in the coming years and hence the survey cannot be expected to give an accurate prediction of the testing pattern for the ETW in the 1990's but it is a valuable guide.

The possible modes of operation have been considered in the light of productivity, nitrogen consumption and costs. A number of 5000 polars per year is foreseen, each of about 15 (force polars) to 60 seconds (pressure polars) duration. About 3 runs per day of approximately 10 minutes and 10 polars each are considered at about 2 hour intervals for model access, modification and re-installation.

A typical operating sequence during a testing day is presented in figure 14. It is envisaged that the facility will be kept mostly at low temperature, ambient temperature testing being done in connection with the few warm-ups per year for maintenance.

5. GENERAL DESCRIPTION OF ETW

The aerodynamic circuit of the tunnel is shown in figure 15. The test section is a slotted wall configuration with the possibility for a later change to a concept of adaptive walls.

Situated in the high speed diffuser, just downstream of the model support sector is a vertical centre body second throat. The liquid nitrogen injection nozzles are in the first cross-leg. The two-stage compressor is situated downstream of the second corner and is driven by a 50 MW electric motor. Gaseous nitrogen is vented from the circuit in the second cross-leg, passed through a silencer, mixed with atmospheric air and discharged from a 50 m stack. The fourth corner is followed by a two-step wide-angle conical diffuser with a total included angle of 50°. A screen is located at the kink to reduce the possibility of separation. The stilling chamber containing the screens and a honeycomb is followed by a contraction with a modified sine-law area distribution and an area ratio of 12. A movable block, single jack nozzle is provided for the Mach number range 1.0 to 1.3. The complete tunnel circuit is enclosed within a reinforced concrete cold box.

An artist's impression of the windtunnel is given in figure 16. Apart from the tunnel in its cold box it shows the model handling hall, the office building and the building containing the workshops.

Also shown are the LN_2 reservoir, an air separation plant for the production of LN_2 and the stack for discharge of the gaseous nitrogen into the atmosphere.

6. DESIGN FEATURES

6.1 PRESSURE SHELL AND COLD BOX

A drawing of the pressure shell is presented in figure 17. The shell will be of welded construction fabricated from austenitic stainless steel and will incorporate a removable flange bolted section at the compressor.

The shell will be supported by spherically ended vertical struts, constrained by lateral guides and anchored at the fixed point of compressor which also provides the thrust reaction.

The complete tunnel circuit will be contained within a reinforced concrete "cold box" which will incorporate a number of removable roof panels for access to major equipment (Fig. 17).

To achieve the necessary cryogenic environment for the pressure shell the "cold box" will be lined with fibre glass insulation blankets to a total thickness of 0.4 m. The blankets will be covered with a fine mesh stainless steel wire screen and faced finally with perforated stainless steel sheet.

6.2 NOZZLE AND TEST SECTION

A study undertaken to determine the type of variable nozzle to be employed in ETW has indicated a movable block, single jack nozzle (Fig. 18) as being the most suitable for the cryogenic environment. The study concluded that whilst the multi-jack nozzle would give the better flow quality in an ambient tunnel, in a cryogenic environment there is a limitation to the level of flow quality that can be achieved due to the restriction of measurement accuracy of the flexible plate position. This applies equally to both concepts. To keep the tunnel systems as simple as possible it was therefore decided to opt for the nozzle with the fewest moving parts in the cryogenic environment.

The nozzle fixed point is at the entry to the test section, all thermal movement of the plate is from this point. To allow for this, and the movement due to flexing of the plate, the movable block is hinged part way along its length. This along with the double hinge link at the upstream end allows translation of the plate without any step discontinuities at the junction with the contraction. The position of the movable block sets the Mach number in the test section and the actuator on the free part of the flexible plate sets the longitudinal distribution.

With this system the Mach number within the test section volume is expected to be within a 3σ value of 0.008 throughout the supersonic regime.

A specialist working group was set up to recommend to the technical group:

- a test section wall configuration for incorporation in the initial design of ETW
- what type of advanced configuration should be considered for possible installation at a later date.

This working group sought to find a wall configuration which would give: acceptable low residual flow inhomogeneity (flow curvature $<$ 0.030 degree/chord; spanwise variation in flow angle $<$ 0.10 degree) and would enable flow measurements to be made for the calculation of wall interference for both sting mounted, complete model and floor mounted half model tests.

The conclusions of this working group are:

1) no form of adaptive wall is sufficiently well validated for three dimensional testing through the subsonic- transonic- low supersonic speed range to permit its consideration for the first build of ETW
2) there is no form of conventional (non-adaptive) ventilated wall which meets the ETW requirements on all counts. On balance the adoption, for the initial build, of four slotted walls is preferred and a configuration with 4 slots in the side walls and 6 slots in the top and bottom walls is recommended.
3) in the design of ETW provision should be made for quick and easy retrofit of flexible horizontal walls to allow a degree of wall adaption to be used to reduce wall interference at subsonic and transonic speeds.

The porosity of the slotted walls can be varied from 0 to 18% per wall by manually changing slot inserts.

The top and the bottom walls are remotely and independently adjustable from -0.5 to +1.0 degree.

The re-entry area consists of tapered finger flaps, hinged at their downstream end. The set of flaps for each wall are remotely adjustable from -7 to +15 degrees for the top and bottom walls and from 0 to +15 degrees for the side walls.

The slats are attached to the back-up structure and fixed at their upstream end in such a way that they can expand and contract freely due to differential temperature effects.

Similarly, the nozzle is fixed at its downstream end and supported along its length so that it can freely expand and contract when temperature differences occur.

6.3 SECOND THROAT

The second throat concept is shown in Fig. 19. Its purpose is to reduce flow disturbances propagating upstream from the high speed diffuser and downstream area and to give faster Mach number control during model traverses. The vertical centre body, variable geometry second throat will be installed directly behind the model support sector. The sector fairing is attached to the model cart. When testing half models an elliptical fairing, attached to the model cart will be positioned in front of the second throat. This double hinge concept was selected to reduce shock losses and to have the capability to adjust the initial shock position so that the throat remains sonic throughout the polars for a wide variety of models. The second throat will be operational for test section Mach numbers between 0.6 and 1.0.

6.4 MODEL ACCESS AND HANDLING

As mentioned earlier, the ETW productivity target is for 5000 test polars to be carried out per year using single shift working. Sophisticated model access and handling arrangements will be necessary to achieve this.

An interchangeable model cart system is planned. A cart will be removed from the tunnel to a safe human working environment for adjustments or changes to the model. Four carts are planned, 3 sting support carts and 1 half-model cart.

A typical sting support cart is drawn in figure 20. For sting supported models, circular arc struts will be used giving pitch angles from -10° to +35 degrees.

The lower part of the plenum is reinforced to permit a large opening to allow for the passage of the model cart to the test section (Fig. 21). This opening can be closed by the model cart lift platform which also functions as the pressure gate. A pressure seal is located in the lower surface of the access opening and the lift gate reacts the pressure load. The lift gate and the model cart are raised by four electrically-driven ball-screws. The lift gate is held in final position by sixteen locks. The model cart is lifted off the lift gate by four actuators and held against mechanical stops to attain final alignment of the model in the test section. The tunnel is depressurised each time the model is removed from the test section.

One of the consequences of the choice of the model access system chosen is that the tunnel centreline will be about 19 m above ground level. A schematic drawing of cold box, pressure shell and model access system is given in figure 22.

Figure 23 shows the layout of the part of the ground floor of the building associated with model handling. The workshops, the model and cart rigging bays and "warm hall" are regions of human access. The cold hall will be a nitrogen area. The transfer lock provides environmental isolation between them. Air in the "warm hall" will be very dry at all times. There will be a changeover from ambient (i.e. moist) air to very dry air in a cart rigging bay a few hours before the cart is due to go into the cold hall. This atmospheric control is intended to minimise any moisture contamination problems in model and cart when they are cooled. Carts are driven between the rigging area and the cold hall on the transfer cart. Once in the cold hall, the cart goes for cooldown into one of the "temperature conditioning rooms" (TCR's) or into the "variable temperature check-out room" (VTCR).

Figure 24 shows schematically what could be a possible system for model temperature conditioning. The proposed system requires minimum alteration of the presently conceived model handling and room arrangement. The system consists basically of a small closed circuit atmospheric low speed tunnel located in the "quick change room" (QCR) attached to TCR2. The test section would be 0.6 m wide by 1.8 m high and could be made suitable for both a sting mounted model (rolled at 90 degrees) and a half model. At the penetration between QCR and TCR2, 2 remotely operated doors could be open to let the model in and out or closed and sealed around the sting, thus providing a simple and remotely controlled model access system. In order to achieve a moderate forced convection environment in the conditioning section at atmospheric pressure, a Mach number of 0.1 is required.

The proposed sytem is thought to be relatively simple to incorporate in the present building and facility layout, simple to operate and sufficiently flexible in as much as the conditioning flow is of variable temperature and speed (and therefore variable heat transfer coefficient). In addition to the small conditioning tunnel with its fan and drive, it requires a LN_2 injection system, a GN_2 exhaust system, and a LN_2 tank. GN_2 could be either recovered or released through the GN_2 low pressure vent stack. Being a non pressurized circuit, the tunnel could be of relatively cheap construction.

The model temperature conditioning tunnel could be used for model warm up as well as for cool down. In the warm up mode, the LN_2 injection system could be either switched off to allow the gas temperature to raise to any desired level through the action of fan power or, when the flow temperature level is reached, controlled to keep the desired temperature. It is estimated that to raise the flow temperature from 100 K up to ambient, it would take about 4 minutes, at $M = 0.1$ and atmospheric pressure, with a fan power of about 150 KW.

Adjustments or changes between runs to a sting mounted model can be accomplished in the QCR attached to the TCR (Fig. 25). It is anticipated that the QCR will be used for routine changes or adjustments which might take an hour or so to complete. A breathable (dry air) atmosphere will be provided in the QCR before human entry. After model work is complete and personnel have left the model is cooled down again. Critical model temperatures will be monitored during warm up and cool down.

It is expected that the warm up and cool down times for the half-model will be considerably longer than those for the sting mounted model.

In view of the probable complexity of the models and the high cost of tunnel operation, great efforts will have to be made to achieve reliable operation of all model and cart systems. This will be the main function of the variable temperature check-out room (Fig. 23), where a complete pre-test check-out at any temperature will be possible. The VTCR can also be used simply for cart cooldown, if required.

6.5 COMPRESSOR AND DRIVE SYSTEM

The compressor has to operate over a large speed range in the cryogenic environment as well as at ambient temperatures. Efficiencies should be high as the losses are not only paid for in terms of compressor energy consumption but also in additional LN_2 use. These requirements have presented some difficulties for the aerodynamic and the mechanical design of the unit.

The compressor has two stages with inlet and outlet guide vanes, the inlet guide vanes being variable to provide full control for the compressor which is mainly speed controlled.

The drive system for the compressor has to provide a maximum power of about 50 MW.

The need to perform fast set point changes between tests to save LN_2, requires a 30 % overtorque capability of the motor. A synchronous motor fed from a 50 Hz power source was chosen as a relatively simple and reliable prime mover.

6.6 NITROGEN SYSTEMS

Liquid nitrogen will be used for cooling of the tunnel. Based on the required productivity and the expected test spectrum it is estimated that about 70,000 tonnes of LN_2 will be needed annually. A reservoir capacity of about 3000 m^3 is required.

A schematic of the LN_2 system is presented in figure 25.

The test requirements include significant transient flow rates in addition to steady-state requirements. A pressurized tank design is chosen to assure good control and reliability of LN_2 injection. A schematic of the LN_2 injection system is presented in figure 26. The main injection control is by a digital valve with secondary nozzle unit selection by on-off valves.

Gaseous nitrogen will be blown off from the second cross leg, through a manifold surrounding the ducting. Via a silencer, the nitrogen is led into the exhaust stack where it is mixed with surrounding air. The mixing is forced by two fans and by an ejector system which draws outside air into the stack (Fig. 27).

The mixture of GN_2 and air is blown into the atmosphere at an adequate velocity to prevent any safety and fogging hazards. The exhaust stack will be about 4.4 m in diameter and about 50 m high.

6.7 ENVIRONMENT

A noise study undertaken recently has indicated that the noise level from the facility throughout the operating envelope will be within acceptable limits in both the near and far field regions.

7. PILOT TUNNEL

The pilot tunnel (PETW) is a scaled-down (1:8.8) version of ETW. It has been installed at NLR, Amsterdam. The main characteristics are shown in figure 28. After the end of the acceptance tests it will be used to check the aerodynamic performance of the ETW circuit (losses, diffuser performance, need for a second throat), to perform control studies in order to validate mathematical models used for ETW control studies, and to gain operational experience with a transonic cryogenic tunnel.

An artist's impression of the tunnel in its cold box is given in figure 29.

The test section (Fig. 30) is equipped with slotted walls (6 slots on top and bottom walls, 2 slots on sidewalls). All 16 slots are 5 mm wide (8% open area ratio average) linearly tapered at the upstream end and equipped, at the downstream end, with adjustable finger type re-entry flaps. Whilst ETW will have a flexible nozzle the PETW nozzle is formed by interchangeable pairs of contoured blocks, one for the subsonic regime, one for M = 1.2 and one for M = 1.35. The Mach number range is: .3 to 1.35. The temperature range is: 90 K to 310 K. The pressure range is: 1 to 4.5 bar.

The fan has two stages with blading based on the NACA 65 series. Each stage has 34 rotor blades and 43 stator blades with provision for changing the stagger angle.

The tunnel shell and most of tunnel components are made from alluminium alloy. Pairs of thermocouples are fitted at locations where large temperature gradients could occur during the cool-down or warm-up process. Thermal stresses can be kept to an acceptable level if the temperature difference is controlled accordingly.

The complete facility (including the drive system) is supported on a baseframe mounted on anti-vibration mountings. The shell is attached to the baseframe at 4 locations with a fixed anchor point at the fan. The support system allows axial movement of the fan leg while the rest of the circuit can move in any horizontal direction.

The drive system consists of a 1 MW variable speed dc motor and a gearbox with a ratio of 1:6.75. The maximum output shaft rotational speed is 9000 revolutions per minute. The drive is rated for intermittent operation of 30 minutes at full power followed by 60 minutes cooldown.

The tunnel insulation is mainly of the cold box type, except for around the nozzle and the plenum where individual removable insulating blocks are applied. The cold box is made of adapted standard modular panels of rigid polyurethane foam 100 mm thick, sandwiched between two thin aluminium plates. Panels are internally lined with a 50 mm thick layer of phenolic foam covered with mylar. During tunnel operation, the cold box is continuously purged with nitrogen and maintained slightly above atmospheric pressure to prevent ingress of moisture.

Figure 31 shows how the PETW is installed in its building, whereas figure 32 shows PETW with its nigrogen blow-off system and the cold box partly removed.

The liquid nitrogen is stored in a 28.5 m^3 tank. The liquid transfer system is sized for a maximum mass flow of about 6.5 kg/sec. Transfer is achieved either through a constant speed pump or by tank pressurisation. For safety and environmental reasons, the exhaust pipework is fitted with a 0.375 MW gas heater and a silencer.

The data system is organised around a HP 1000 computer with peripherals (printer, vdu, x-y plotter, disk).

The control system is manual. The tunnel will be operated from a control desk located in an enclosed air-conditioned cabin in the tunnel room. Briefly, the system includes controls and displays for:
- liquid nitrogen injection
- gaseous nitrogen exhaust
- tunnel and cold-box purging systems
- the drive and its auxiliary systems
- the fan and its auxiliary systems
- oxygen level monitoring in all rooms around PETW

8. AERODYNAMIC CIRCUIT TEST RIG

In order to check the aerodynamic performance and flow quality of ETW it was decided to construct a test rig although it was realised that the Reynolds number would be about 2 orders of magnitude lower than in ETW. It was constructed, and the tests were conducted by DFVLR Köln-Porz under contract to ETW.

The flow quality goals for ETW are presented in figure 33. ETW is designed to provide aerodynamic data of high standard in a relatively short running time. This implies that the flow quality has to be excellent and the specification is framed accordingly. The test rig (Fig. 34) is a model windtunnel simulating the ETW circuit starting from the cross-leg up-stream of the settling chamber, through the complete high-speed leg and the following cross-leg to the compressor inlet section. The back-leg has been opened to be able to run the rig in a blow-down or suction mode. The working fluid is ambient temperature air. The scale of the rig with respect to ETW is the same as that of PETW (1:8.8). A photograph of the test rig is given in figure 35.

The following measurements and investigations were conducted:
- longitudinal static pressure distribution along the test rig on the upper and inner walls
- total head surveys at several stations
- flow angularity and Mach number distributions in the test-section
- boundary-layer development in the high speed diffuser with and without highly-disturbed inlet flow, with and without diffuser blow-off
- visualisation of flow separations
- unstationary pressure fluctuations and turbulence.
- noise measurements (power spectral densities, coherence and phase spectra) with and without choking at the end of the test section.

Some typical test results are presented in figure 36 (Mach number distribution in test section at M = 0.85) and figure 37, which shows a typical flow angularity distribution.

Figure 38 provides a comparison of total head losses as measured in the test rig with calculations.

The noise measurements demonstrated that sound from downstream of the test section is the dominant contribution to the pressure fluctuations in the test section and that this can effectively be cut off by choking the tunnel at the end of the test section. Figure 39 shows the pressure spectra for the choked and the unchoked cases at M = 0.8 in the test rig.

In general, the conclusion from the test rig results is that the flow quality and aerodynamic performace goals of ETW appear to be met.

9. FUTURE DEVELOPMENT

At the time of writing all four participating countries have expressed their interest in continuing the project and have agreed upon the site to be at the DFVLR establishment in Cologne.

Presently the go-ahead and signing of the MoU is awaited for the next phase (Phase 2.2) of the project, which will be the writing of the Requests for Proposals for the various construction work packages. This phase is now expected to start mid 1985 and to last 2 years. Following this tendering, detail design and construction will take approximately 6 years followed by commissioning and calibration, each being of 1 year duration.

The overall expected time schedule of the project is shown in figure 40.

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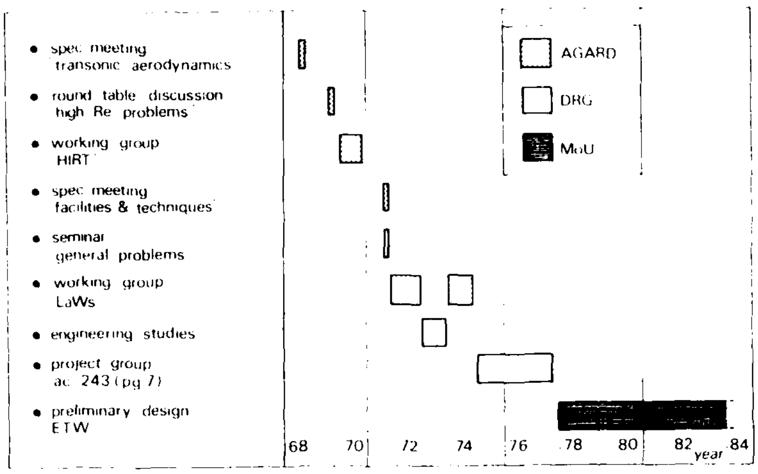

FIGURE 1 ETW history

$25 \times 10^6 < Re_c < 40 \times 10^6$

maximum 6 bars

test section $5 \times 4.2\ m^2$

run time 10s

good flow quality

FIGURE 2
LaWs specification

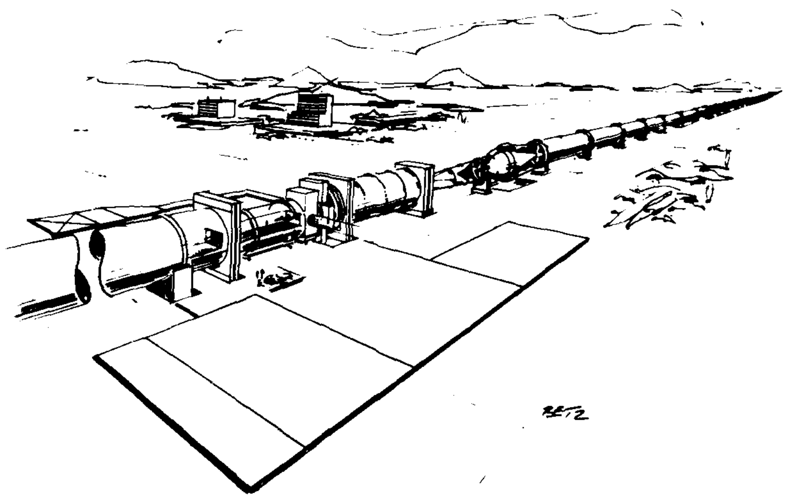

FIGURE 3 The Ludwieg Tube, LT

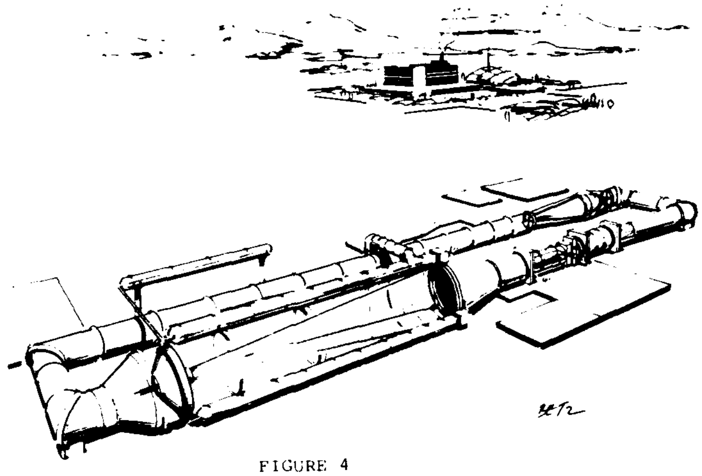

FIGURE 4

The Evans Clean Tunnel, ECT

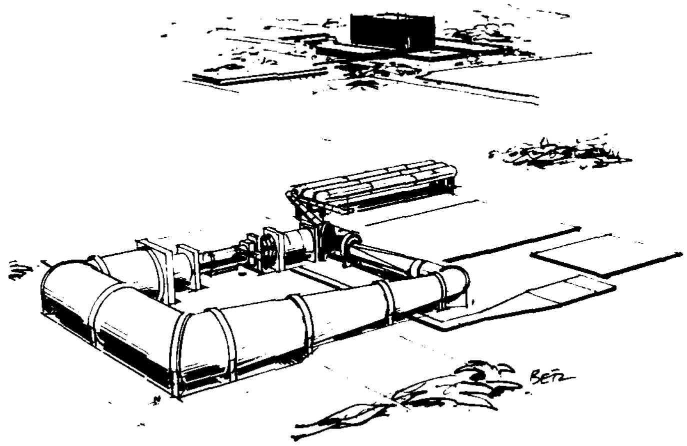

FIGURE 5

The Injector Driven Tunnel, IDT

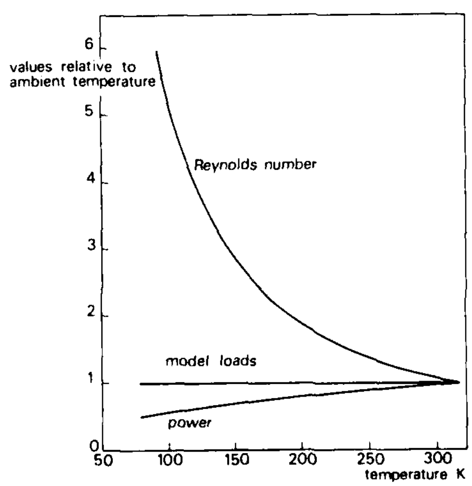

FIGURE 6

Influence of temperature on Reynolds number, power and model loads

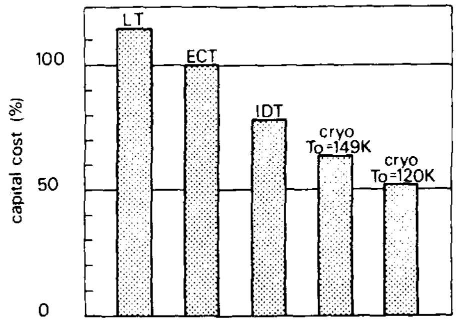

Figure 7 Comparisons of capital costs of ETW options

test - section dimensions	2.4m × 2.0m
Mach number range	0.15 - 1.3
operating pressure range	1.25 - 4.5 bar
operating temperature range	90 - 313 K
fan drive power	50 MW
productivity	5000 polars/year minimum

FIGURE 8 ETW specification

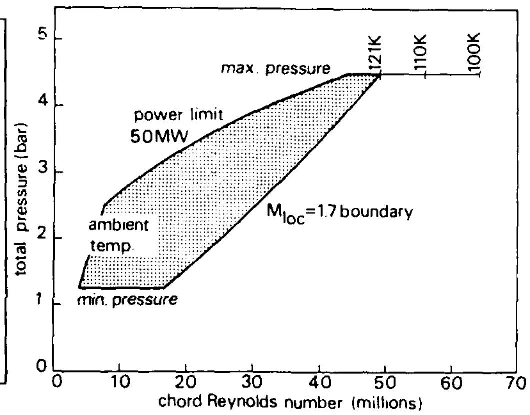

FIGURE 9 ETW operating envelope at M=0.9

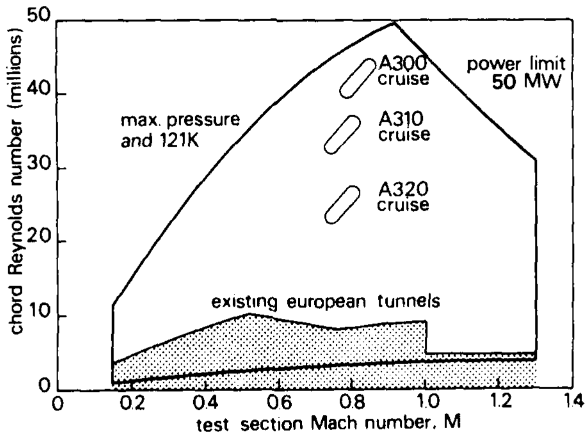

FIGURE 10

Reynolds number performance of ETW compared to existing European facilities

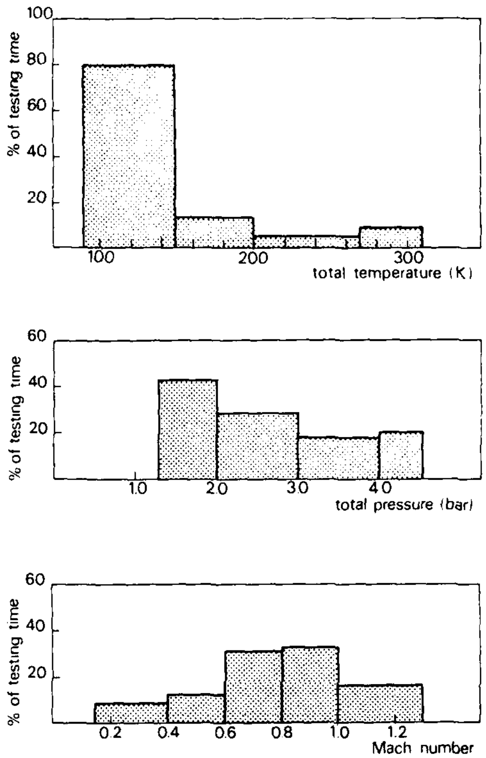

FIGURE 11

Forecast of distribution
of testing time

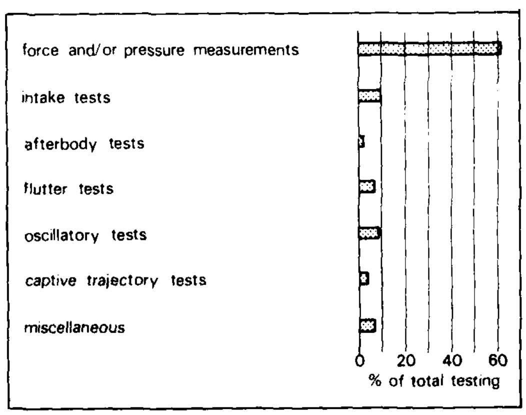

Figure 12 Forcast of distribution
of types of test

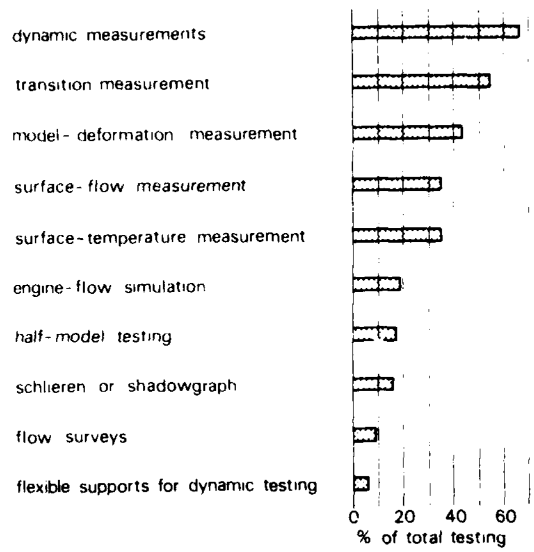

Figure 13 Forcast of distribution of testing technique

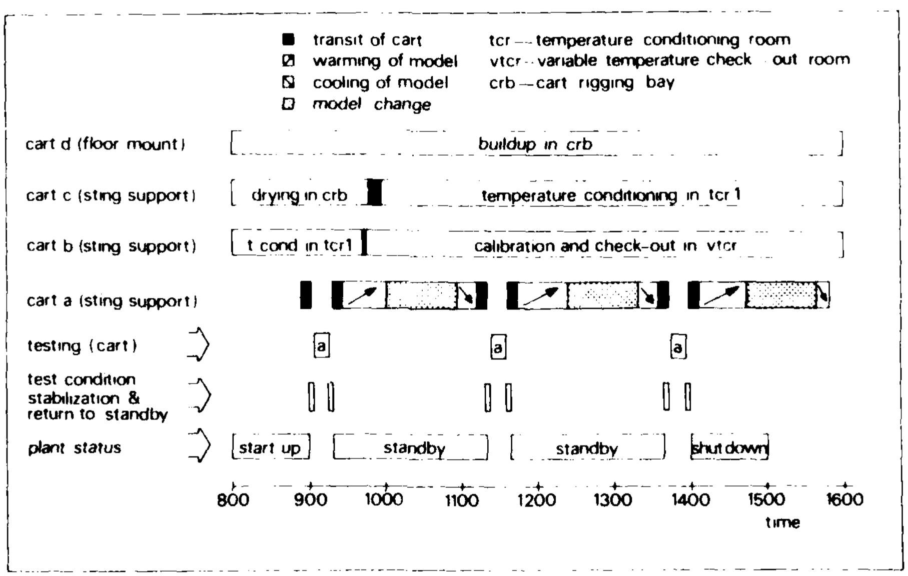

Figure 14 Operating sequence

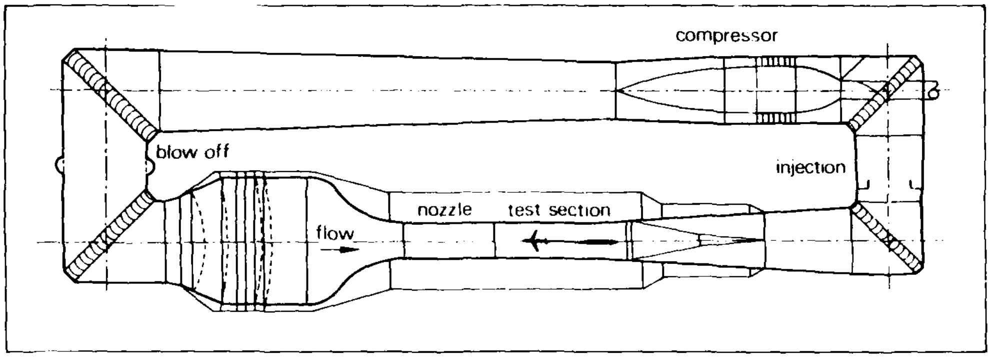

FIGURE 15 Aerodynamic circuit

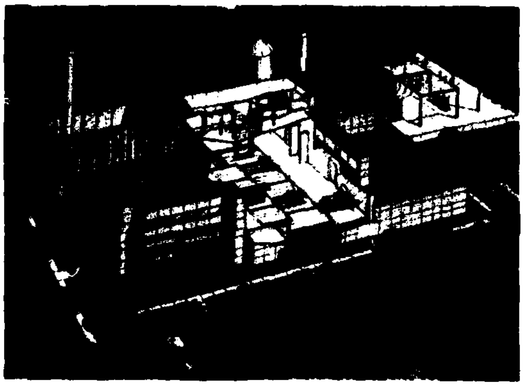

FIGURE 16 Artist's impression of ETW

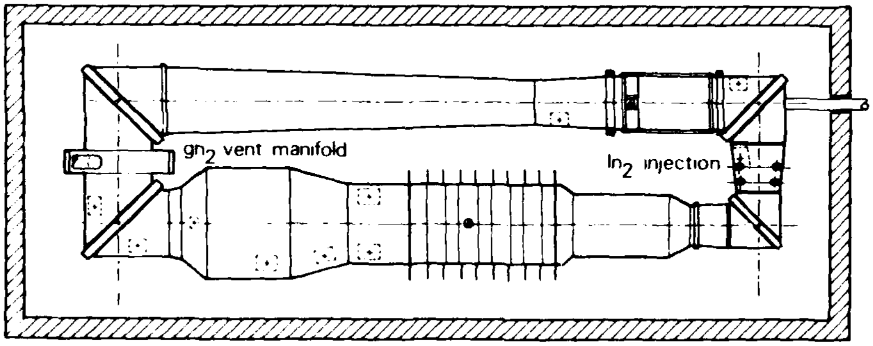

FIGURE 17 Pressure vessel and cold box

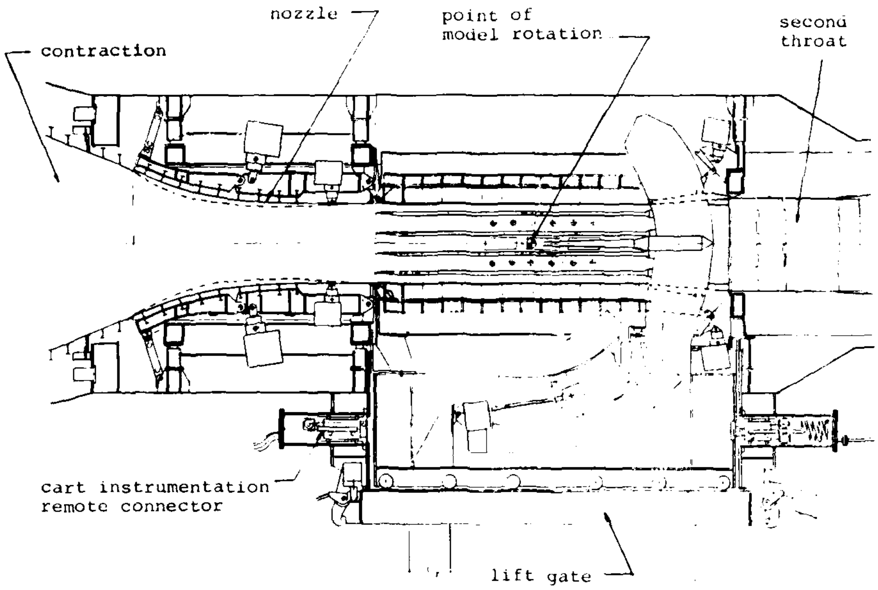

Figure 18 Nozzle and test section

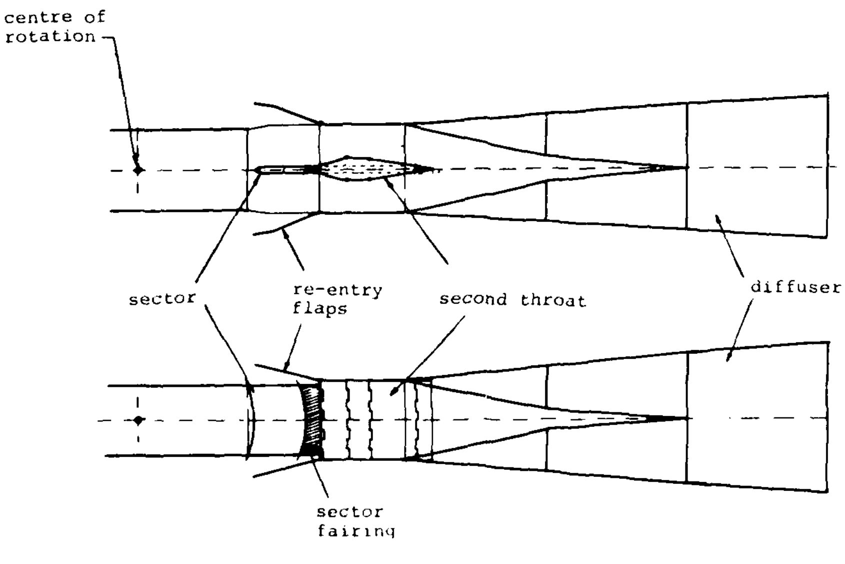

Figure 19 Second throat and high

speed diffuser

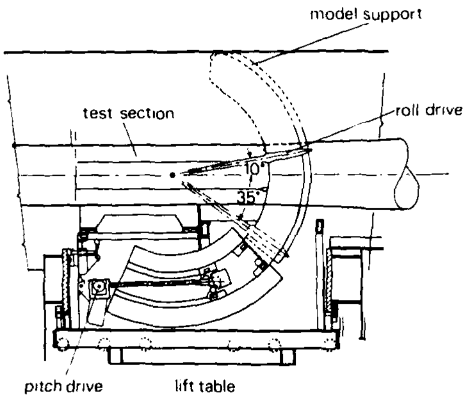

FIGURE 20
Typical model support

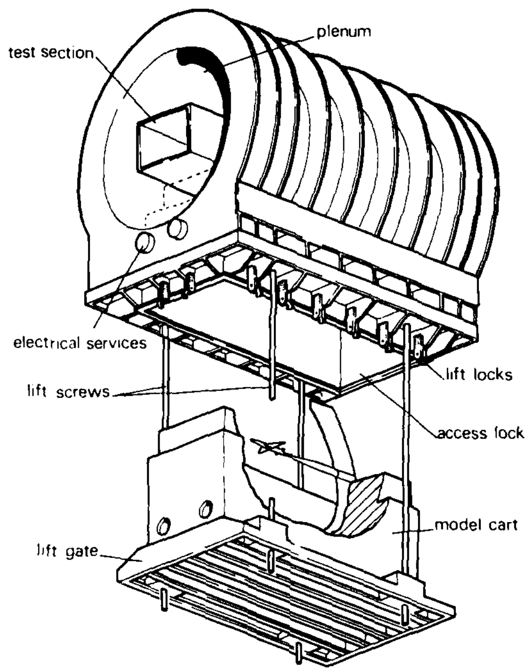

FIGURE 21
Model access

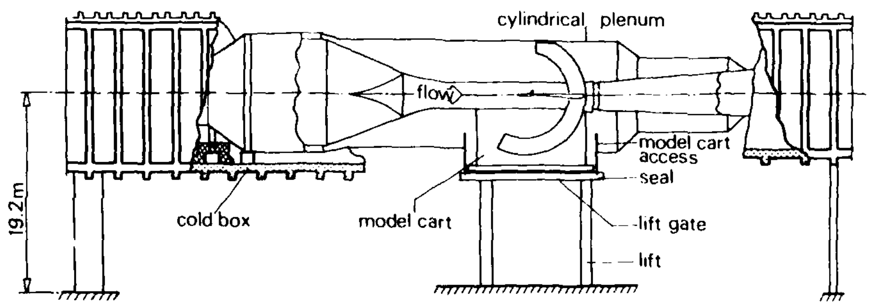

FIGURE 22 Schematic of coldbox, pressure shell and model access

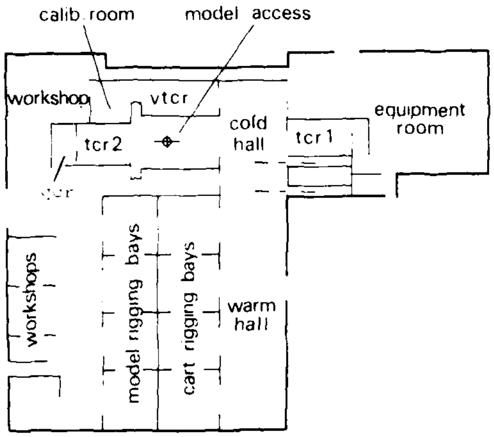

FIGURE 23
Support building layout

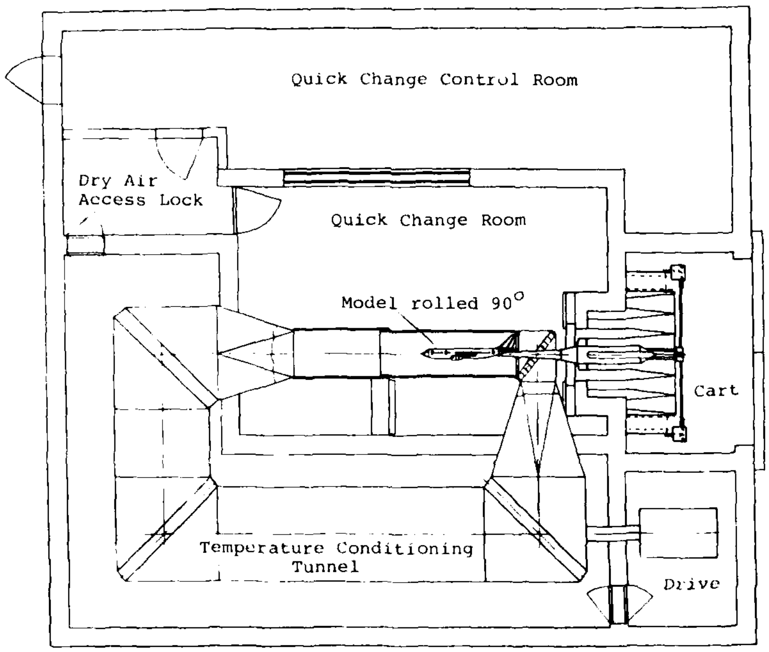

Figure 24 Quick change room and model temperature conditioning system

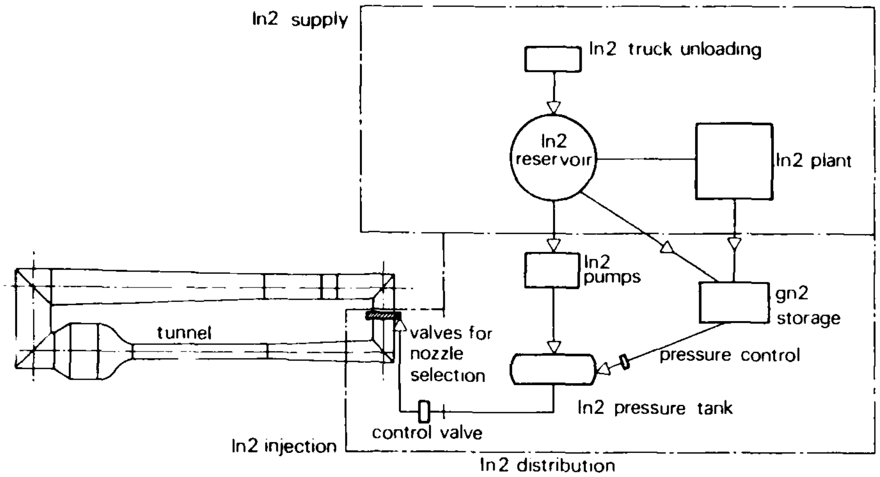

FIGURE 25 Schematic of liquid nitrogen system

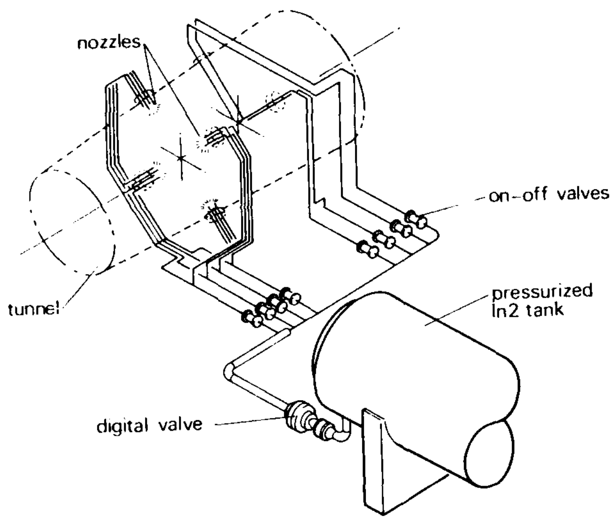

FIGURE 26
Liquid nitrogen injection system

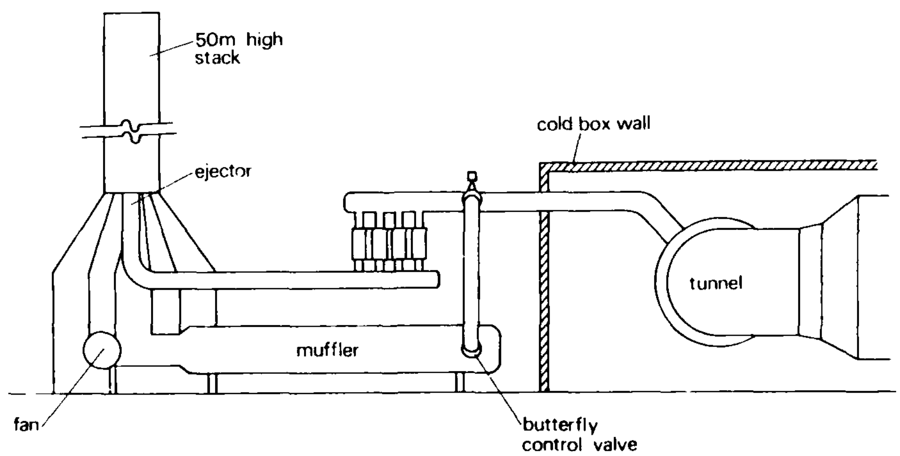

FIGURE 27 Exhaust system

test section	0.23m x 0.27m
Mach number	0.35-1.0 continuous
	1.2
	1.35
operating pressure	1.25-4.5 bar
operating temperature	90-313K
fan drive power	1 MW

FIGURE 28
PETW specification

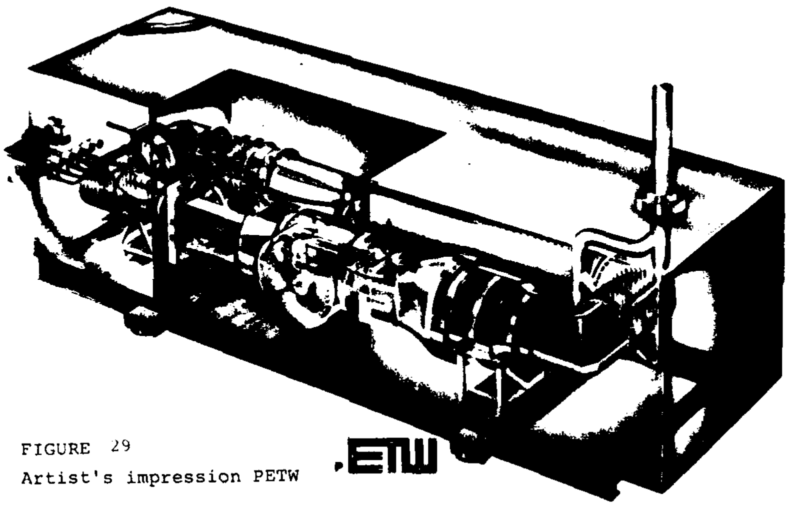

FIGURE 29
Artist's impression PETW

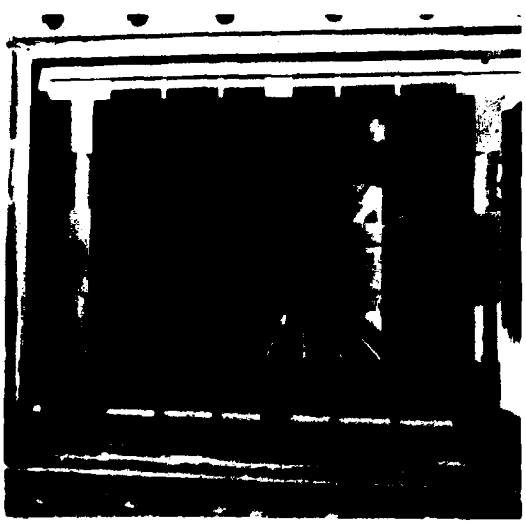

FIGURE 30
PETW test section

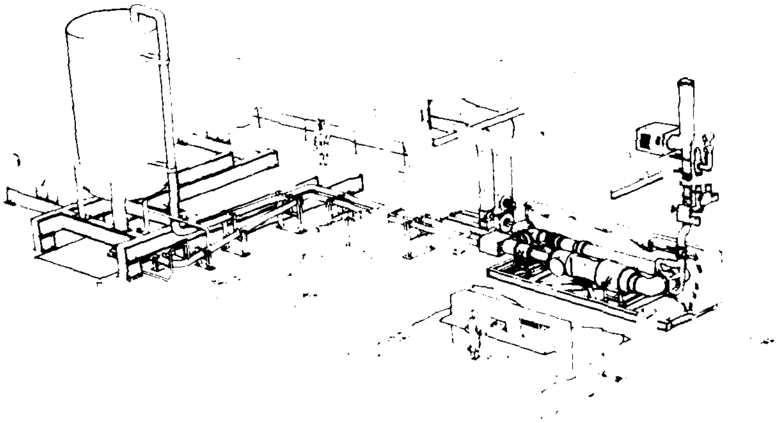

FIGURE 31
PETW layout

FIGURE 32 PETW with cold box partly removed

turbulence level	0.05 %	
Mach number deviations	± 0.001 subsonic	3 σ values
	± 0.008 supersonic	
total temperature deviations	± 0.25 K	
test-section noise level	about turbulent boundary-layer noise	

FIGURE 33 ETW flow quality requirements

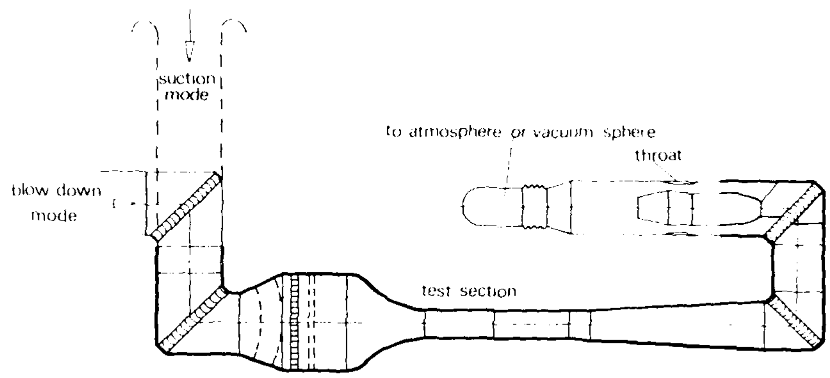

FIGURE 34 Test rig circuit

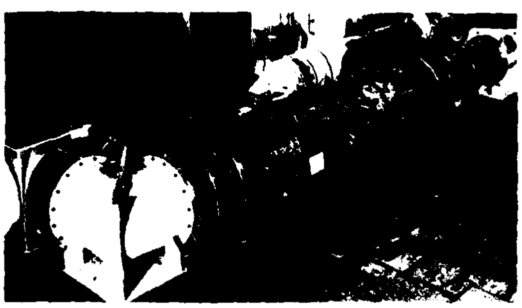

FIGURE 35 Photograph of test rig at DFVLR

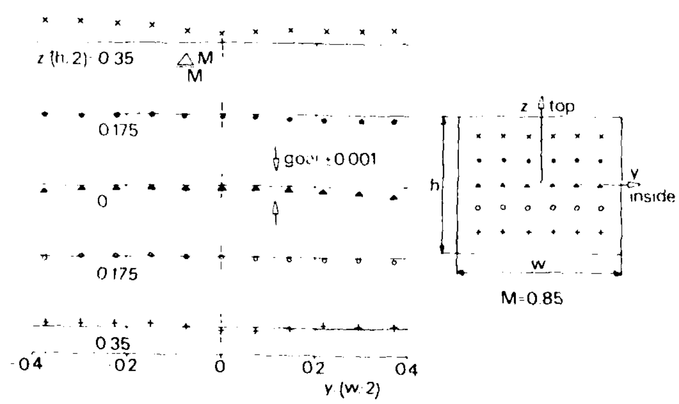

FIGURE 36 Typical Mach number distribution

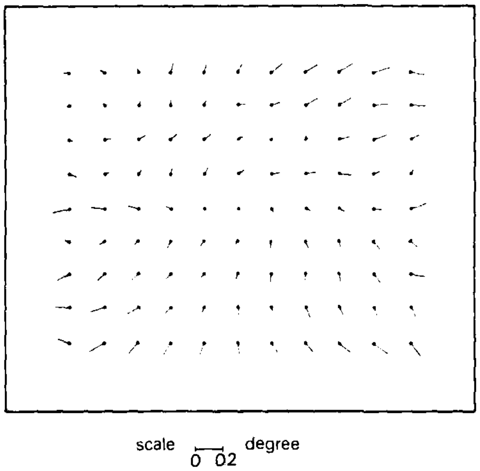

FIGURE 37
Typical flow inclination distribution in test section

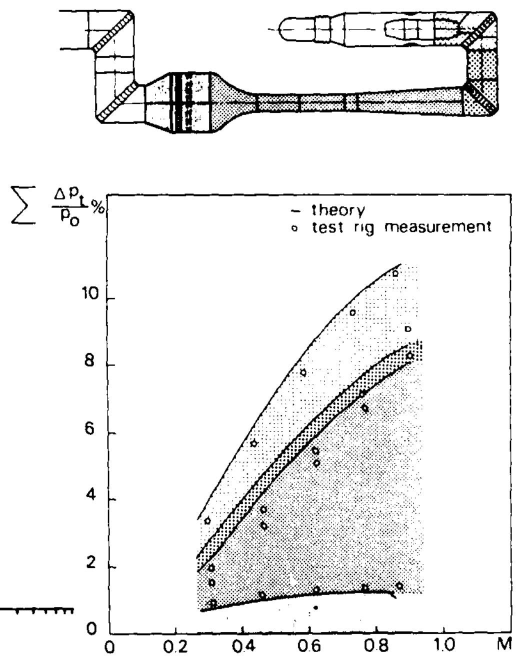

FIGURE 38
Comparison of measured and calculated total head losses

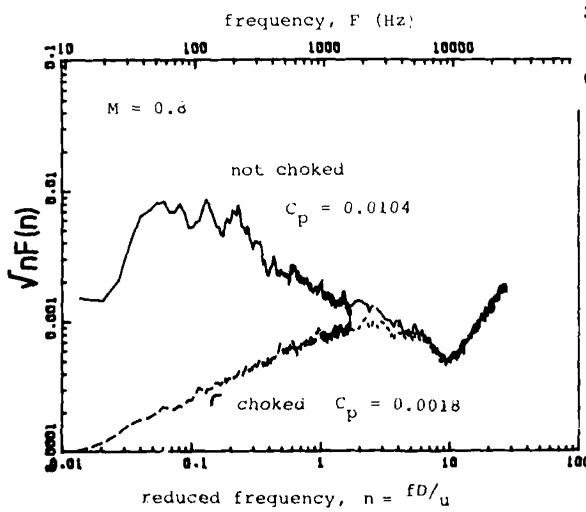

Figure 39 Pressure spectra in test section with and without choking at downstream end of test section

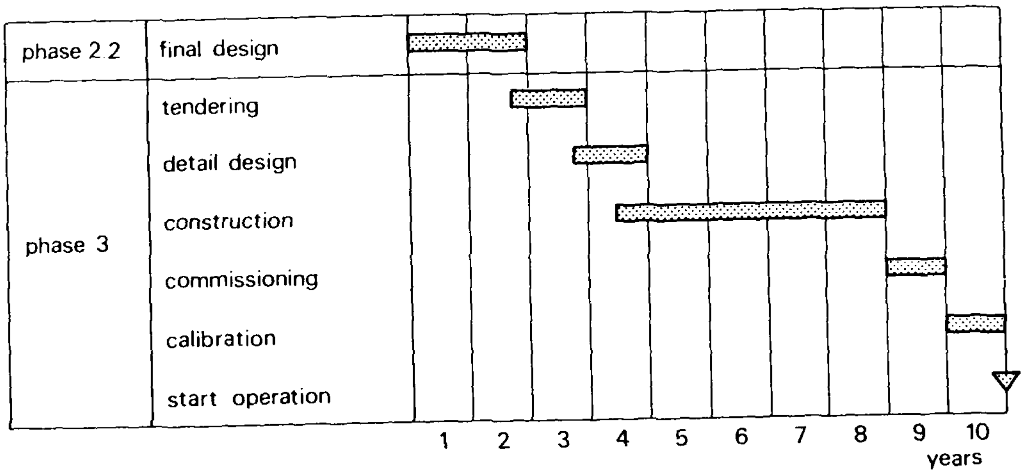

FIGURE 41 ETW time schedule

THE NASA LANGLEY 0.3-m TRANSONIC CRYOGENIC TUNNEL

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SUMMARY

The Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) can operate from ambient to cryogenic temperatures at absolute pressures from 1 to 6 bars. Since the 0.3-m TCT began operation in 1973, it has been used to develop instrumentation and operating techniques for cryogenic tunnels as well as for aerodynamic tests where advantage can be taken of the extremely wide range of Reynolds number available.

This paper describes the present capabilities of the 0.3-m TCT and gives an overview of recent research activities which include both steady and unsteady testing. Emphasis is given to safety and the development of testing techniques for cryogenic tunnels. Results of studies aimed at establishing the lower limits of operating temperature are presented and the impact of these studies on tunnel operation is discussed. Finally, the design features and operating characteristics of a new self-streamlining wall test section recently installed in the tunnel circuit are described.

1. INTRODUCTION

Following the successful completion of the Low-Speed Cryogenic Tunnel studies at the Langley Research Center in the summer of 1972, it was decided to build a relatively small fan-driven transonic cryogenic pressure tunnel in order to extend our experience with cryogenic tunnels to the pressure and speed range contemplated for a large high Reynolds number transonic cryogenic tunnel. The purpose of the Pilot Transonic Cryogenic Tunnel was to demonstrate in compressible flow that Reynolds number dependent aerodynamic phenomena behave in the same manner when a given Reynolds number is obtained by temperature as when obtained by pressure; to demonstrate the method of cooling at the relatively high fan-drive power levels required for transonic operation; to determine any limitations imposed by liquefaction of the test gas; to verify engineering concepts with a realistic tunnel configuration; and to provide additional operational experience beyond that provided by the low-speed tunnel.

Design of what was to be known as the Pilot Transonic Cryogenic Tunnel began in December of 1972 and initial operation began in August of 1973. The first run at cryogenic temperatures (172 K or lower) was made on October 16, 1973, less than 2 years after work was started at Langley on the cryogenic wind tunnel concept.

The Pilot Transonic Cryogenic Tunnel has been outstandingly successful in fulfilling the purposes for which it was built. It has been made an "official" NASA facility, renamed the Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) and is now seeing service in a wide range of experimental programs. These programs include research in aerodynamics and cryogenic wind tunnel technology.

It is the purpose of this paper to report on some of the more significant design and operational aspects of the 0.3-m TCT as well as some of the more recent test results. In addition, this paper will describe modifications presently being made to the tunnel to fit it with a two-dimensional adaptive wall test section.

2. DESCRIPTION OF THE 0.3-m TRANSONIC CRYOGENIC TUNNEL

As noted in the introduction, the tunnel now known as the 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) started out being known as the Pilot Transonic Cryogenic Tunnel. The basic tunnel structure has not been altered in the 11 years since it was built. However, the original test section has been changed and a continuous series of changes have been made to the control, instrumentation, and data acquisition subsystems and to the tunnel operating procedures. In the sections which follow, an a[illegible] will be made to differentiate between the original tunnel configuration and its subsystems and the present tunnel and its improved subsystems.

2.1 General Description

A sketch of the 0.3-m TCT is shown in Figure 1. The 0.3-m TCT is a fan-driven tunnel originally fitted with a slotted octagonal test section which was 34.3 cm between flats. This was a scaled down version of the test section used for the Langley 16-Foot Transonic Tunnel before it was equipped with a plenum suction system. It was in this test section that the transonic cryogenic tunnel "proof of concept" tests were made.

The fan is driven by a variable speed, 2.25 MW electric motor. In its original three-dimensional configuration, the tunnel could be operated at Mach numbers from near 0.05 to about 1.3 at stagnation pressures from slightly greater than 1 bar to 5 bars over a temperature range from 340 K to about 77 K. The ranges of pressure and temperature made it possible to investigate almost a 5 to 1 range of Reynolds number effects by independently varying either pressure or temperature.

The tunnel pressure shell is made of plates of 6061-T6 and 5083 aluminum alloys which were either bent or machined to shape and welded to form the different sections of the tunnel. The sections are joined together by bolted flanges sealed with a wide variety of suitable gasket materials. As shown in Figure 1, the tunnel is fixed at the fan section and allowed to move on sliding joints relative to the fan section to accommodate thermal contraction and expansion.

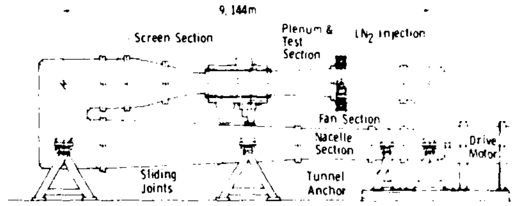

Fig. 1 Sketch of 0.3-m TCT.

2.2 Thermal Insulation System

Except for intermittent cryogenic tunnels having very short run times, such as the cryogenic isentropic light piston tunnel (CILPT) at Cranfield with a run time of 0.3 seconds, cryogenic tunnels are generally fitted with thermal insulation. The insulation system generally satisfies certain requirements for safety as well as operational efficiency. The location of the insulation, whether inside or outside the tunnel structure, as well as the type of insulating material, are determined after careful consideration of many factors peculiar to each cryogenic wind tunnel. This short digression is made to emphasize the important point that the insulation system which has evolved for the 0.3-m TCT is well suited for the 0.3-m TCT, but may not be the optimum thermal insulation system for other cryogenic tunnels. Many of the factors which influence the choice of thermal insulation for a cryogenic wind tunnel are discussed in Reference 1.

2.2.1 Original Insulation System

Since the 0.3-m TCT was the first wind tunnel built specifically for cryogenic operation, there was a tendency toward a very conservative design. This led to a rather complex and expensive thermal insulating system. Basically, the original insulation system consisted of two separate layers of polyurethane foam, each of which was formed in place, separated by two layers of glass fiber cloth. In addition, two layers of cloth separated the tunnel pressure shell from the inner layer of foam. The combined thickness of the foam and the glass cloth was approximately 13 cm. The outer layer of foam was covered with a hard shell vapor barrier of glass fiber reinforced polyester.

Operational experience with the original insulation system soon demonstrated that in order to temporarily remove and reinstall even a small portion of the insulation for inspection, tunnel modification, or repair, the services of skilled technicians had to be procured at considerable expense and tunnel downtime.

Upon removal of the original insulation system during a major modification to the tunnel, large areas of corrosion were discovered on the exterior walls of the aluminum pressure shell. This evidence of moisture condensation was taken as proof of leaks in the vapor barrier and demonstrated the possibility of condensing oxygen on the external tunnel walls at the lower tunnel operating temperatures. Since polyurethane foam is not an oxygen compatible material, the evidence of moisture condensation was regarded as a serious safety hazard which should be corrected.

2.2.2 New Insulation System

As a result of the operational experience noted above, a new thermal insulation system was designed, tested on an unused section of the original 0.3-m TCT, and shown to perform well under conditions typical of those that would be encountered during the operation of the 0.3-m TCT.[1,2]

The thermal insulation system presently used on the 0.3-m TCT was selected based on the requirements noted in Reference 1 as well as experience gained with the original insulation system described above. The present insulation system is actually a combination of insulation subsystems as required by the particular section of the tunnel being insulated. The main insulation system for the tunnel is a simple glass fiber wrap covered by a vapor barrier and slightly inflated by a continuous dry nitrogen purge. The following sections describe the thermal insulation system used on the cylindrical sections of the 0.3-m TCT. Details are given in Reference 1 on how the test section, flanges, supports, and other special sections of the tunnel are insulated.

Insulation material.- Each of the cylindrical sections of the tunnel is wrapped with four successive mats of spun glass fiber insulation. In the uncompressed state, each mat has a thickness of approximately 2.5 cm and a density of about 176 kg/m^3. The mats contain no material other than the glass fiber. Each mat is held together by fiber interlocking which was accomplished during manufacture by repeatedly punching blunt needles through the thickness of the mat. This type of material was selected rather than the more conventional bonded glass fiber mat in order to avoid the introduction of any combustible material into areas cold enough to condense oxygen from the atmosphere.

The insulation was supplied in rolls of 122 cm width, which is less than the length of a typical tunnel section, thus necessitating circumferential butt joints as well as butt joints parallel to the axis of the cylinders. Since there were four layers of insulation, it was possible to stagger the joints to avoid having more than one joint at any given location. Each layer of insulation is held in place by copper wire or thin aluminum bands.

In addition to the four layers of glass fiber mat, an outer layer of woven glass fiber cloth was applied and secured by a tightly wrapped spiral of a 15 cm wide strip of woven glass fiber cloth. The combined compressive action of the copper wire or aluminum bands and the cloth strips resulted in a total insulation mat thickness of approximately 7.6 cm and, with the added woven cloth, a total insulation system thickness of approximately 8 cm.

Vapor barrier.- The woven glass cloth layer and spirally wrapped strip described above formed a stable foundation for the vapor barrier system. The vapor barrier covering the insulation consists of three separate layers applied as a liquid by brush to the spirally wound glass fiber cloth. The first layer is a two component urethane elastomer which serves as a flexible, tough, impact resistant coating which bonds well to the glass fiber cloth. This layer is reasonably impermeable to water vapor and serves as a base for subsequent layers of the vapor barrier system.

The second layer, which serves as the main impermeable membrane of this vapor barrier system, is a two component butyl rubber which has very low water vapor transmission rates, but is soft and has low toughness. The third and outermost layer is chloro-sulfonated polyethylene which serves mainly as a protective coating for the butyl rubber layer.

Purge system.- The entire glass fiber thermal insulation system is maintained at a positive pressure of about 102.01 kPa (0.1 psig) by a purge system to preclude entry of outside air or moisture. The purge gas is dry nitrogen which is readily available from the normal boil-off of the liquid nitrogen storage tanks. The dry nitrogen gas is supplied to a pressure regulator at the purge system supply manifold through an uninsulated copper pipe approximately 30 m long and 5 cm in diameter. Because of the relatively low mass flow rate of the nitrogen purge gas, the heat transfer from the atmosphere to the nitrogen gas through the uninsulated copper pipe is sufficient to raise the gas temperature to ambient by the time it reaches the supply manifold at the tunnel. From the supply manifold, the dry nitrogen purge gas is delivered to each section of the tunnel insulation through small (9.5 mm o.d.) flexible plastic tubes.

The purge gas flows through a perforated copper tube (9.5 mm o.d.) buried in the insulation and running the full length of each of the tunnel sections. In this way, the purge gas is introduced relatively evenly into the glass fiber insulation. The purge gas is collected in a similar perforated tube located 180° around the tunnel section. The flow area provided by the perforations is larger in the outlet tube than the inlet tube in order to guard against any malfunction of the purge gas supply system that would apply an overpressure to the vapor barrier system. In a manner similar to the inlet flow, the outlet flow is collected from each of the tunnel sections through flexible tubes which are connected to an exhaust manifold vented to the atmosphere.

When operating at the lowest temperatures, portions of the tunnel pressure shell can approach the temperature of boiling liquid nitrogen at one atm, 77.35 K. For this reason, the purge gas pressure must be selected with some care. For example, should a purge gas pressure of 108.22 kPa (1 psig) be used, the purge gas will start to condense when the pressure shell wall temperature reaches 78.0 K. By reducing the purge gas pressure to the design pressure of 102.01 kPa (0.1 psig), the wall temperature must be below 77.47 K for the purge gas to condense. This is only slightly higher than the boiling temperature of liquid nitrogen at atmospheric pressure, 77.35 K, thus greatly reducing the likelihood of collecting liquid nitrogen due to condensation of the purge gas within the insulation layer.

Compared to the previous insulation system, the present system was almost an order of magnitude lower in initial installation costs. However, the major advantage of the present system is related to improvements in productivity. The time required to reactivate the insulation system after it has been opened for some tunnel function typically has been reduced from a few days for the previous system to a few hours for the present system.

2.3 Liquid Nitrogen System

A schematic drawing of the liquid nitrogen (LN_2) system as it is now configured is shown in Figure 2. LN_2 is stored at near atmospheric pressure in two vacuum insulated tanks having a total capacity of about 212,000 litres. In the present configuration, the pipes leading from the storage tanks to the LN_2 pumps are a bit too

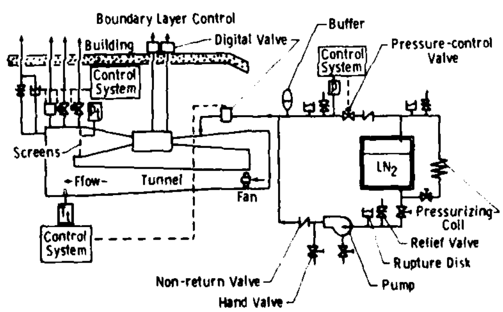

Fig. 2 Schematic of LN_2 system and nitrogen exhaust system.

small, underinsulated, and have too many abrupt turns to permit operation using head pressure only. Therefore, immediately prior to starting the LN_2 pump, the LN_2 supply tank must be pressurized to an absolute pressure of about 1.7 bars in order to maintain sufficient net positive suction head at the pump inlet to prevent cavitation. The larger of two LN_2 pumps is driven by a 22-kW constant-speed electric motor and has a capacity of about 500 litres per minute with delivery at an absolute pressure of about 9 bars. The LN_2 supply pressure is set and held constant by the pressure control valve which regulates the amount of liquid returned to the storage tank through the pressure-control return line.

Tunnel temperature is controlled by a closed-loop feedback control system which regulates the flow of LN_2 into the tunnel circuit.[3] Four identical 10 bit digital control valves[4] operate in accordance with command signals issued from a digital microcomputer-controller. A copper constantan thermocouple located in the settling chamber serves as the temperature sensing element for the digital control system. Due to the wide ranges of tunnel pressure and Mach number, it is necessary to control LN_2 flow rates from about 4 litres per minute to about 500 litres per minute. The 1023:1 turndown ratio provided by the 10-bit digital control valves, in combination with the ability to control the LN_2 supply pressure, makes possible precise control of the LN_2 flow rate and, therefore, precise control of tunnel total temperature over this very wide range.

In its original configuration, the LN_2 supply system did not have the pressure control loop as shown in Figure 2, but rather was dead-ended at the tunnel. This resulted in an excessive cooldown time for the LN_2 pipe leading to the tunnel as well as temperature control problems caused by the boiling of the LN_2 in the supply pipes at the low liquid flow rates required for low-speed operation of the tunnel.

2.4 Nitrogen Exhaust System

The system for exhausting gaseous nitrogen from the tunnel is shown schematically in Figure 2. Tunnel pressure is adjusted by means of an 8-bit digital valve and two hydraulically operated valves in exhaust pipes leading to the atmosphere from the low-speed section of the tunnel. Using this system, stagnation pressure can be varied from about 1.1 to 6.2 bar. A total pressure probe located downstream of the screens provides the reference pressure measurement for the automatic pressure control system.[3]

As originally designed, the nitrogen exhaust from the tunnel vented directly to the atmosphere from pipes carried through the roof of the building housing the tunnel. A severe fogging problem existed with this original design during periods of high humidity and low wind speed. On several occasions, it was necessary to suspend operations until there was a favorable change in the weather.

A simple and effective solution to this problem, for the vast majority of weather conditions, has been found and consists of a simple exhaust driven ejector. The low-pressure ejector induces ambient air which dilutes and warms the cold nitrogen exhaust gas. The resulting foggy mixture is propelled high into the air and dissipates. This simple exhaust ejector, which has an area ratio of about 5:1, induces sufficient ambient air to increase the oxygen level of the mixture to about 11 percent and discharges the mixture so effectively that it has completely eliminated the fogging problem except under the most adverse weather conditions. The ejector is designed so that the mixing of the cold exhaust gas and the ambient air occurs near the outlet of the ejector in order to prevent ice buildup either on the inside or outside of the ejector.[5]

2.5 Results from the Pilot Transonic Cryogenic Tunnel

The Pilot Transonic Cryogenic Tunnel was successfully used to verify the cryogenic wind tunnel concept at transonic speeds and provided much needed design and operational experience for the development of larger cryogenic transonic tunnels.

The most significant experimental study made in the Pilot Tunnel was of a so-called "validation airfoil." Based on the "real-gas" studies of Adcock[6], it was expected that airfoil pressure distributions measured for the same values of Reynolds number and Mach number should be the same at cryogenic and ambient temperature conditions. However, in order to provide experimental verification of this equivalence, the pressure distribution on a two-dimensional airfoil was measured in the pilot tunnel at both ambient and cryogenic temperatures at the same Reynolds number and Mach number by varying tunnel pressure. The almost perfect agreement[7] in the pressure distributions provided the first experimental confirmation at transonic speeds that nitrogen at cryogenic temperatures behaves like a perfect gas and is, therefore, a valid transonic test gas as predicted by the real-gas studies.

The major conclusions with respect to the operation and performance of this tunnel (as both a pilot tunnel and as a proper NASA "facility") after over 5000 hours of operation, mostly at cryogenic temperatures, are as follows:

(1) Purging, cooldown, and warm-up times are acceptable and can be predicted with good accuracy.

(2) The quantity of liquid nitrogen required for cooldown and running can be predicted with good accuracy.

(3) cooling with liquid nitrogen is practical at the power levels required for transonic testing. Test temperature is easily controlled and good temperature distribution obtained by using a simple liquid nitrogen injection system.

2.6 Present Status

In the summer of 1976, the Pilot Transonic Cryogenic Tunnel was fitted with a 20 x 60 cm two-dimensional test section, classified as a NASA "facility" and renamed the 0.3-m Transonic Cryogenic Tunnel, commonly referred to as the 0.3-m TCT. With this two-dimensional test section, the variable fan speed allows the Mach number to be continuously varied from 0.02 to slightly above 0.9.

For two-dimensional testing, the model is rigidly mounted between turntables located in each side wall. There are windows in the top of the plenum as well as windows in the upper portion of the turntable which allow limited viewing of the region above the model. A traversing mechanism may be installed downstream of the model. A total pressure rake is typically installed on the traversing mechanism to measure the wake pressure profile at several span-wise locations to provide drag data and to verify that the flow over the model is two-dimensional. Typically, 5 tubes are used across the span measuring from around the centerline of the model toward one wall.

Upstream of the turntable are two porous plates for sidewall boundary-layer removal. Piping connected to the back side of the porous plate leads to a variable speed compressor. The compressor can remove at least 4 percent of the test section mass flow at all test conditions.

It should be noted that the actuators for the model support turntables and the traversing mechanism are located outside the tunnel in the ambient temperature and pressure environment.[1] The same is true for the pressure instrumentation. Installation of this equipment inside the cryogenic environment has not proved to be reliable. Further details of the 20 x 60 cm test section may be found in Reference 8.

An extensive program was undertaken in 1978 to certify the tunnel circuit for testing at stagnation pressures of about 6 bars absolute rather than the 5 bars absolute for which it was originally designed. This upgrading was considered to be consistent with the strength of the pressure shell and would provide an additional Reynolds number capability as well as the ability to approximate more closely the 8.8 bars absolute stagnation pressure of the U.S. National Transonic Facility.

The tunnel was completely stripped of the original insulation and the entire circuit visually inspected and x-rayed for possible structural damage. It is estimated that at the time of the inspection the tunnel had operated for about 2000 hours and had been subjected to about 600 complete pressure-temperature cycles. The requirements for certification of the pressure shell to a 6 bar absolute pressure operating capability required fairly extensive removal of original welds, rewelding, and testing. However, it should be noted that, even after several years of operation at absolute pressures up to 5 bars, the pressure shell had maintained structural integrity. Following certification for operation at an absolute pressure of 6 bars, the new thermal insulation system described in section 2.2.2 was installed.

With the operating pressure increased to slightly over 6 bars absolute, the 0.3-m TCT became the highest Reynolds number airfoil testing facility in the world with its test Reynolds number capability of up to 400 million per metre. Additional details of the operational characteristics of the 0.3-m TCT are given in Reference 5.

In addition to testing advanced airfoils, the 0.3-m TCT is being used to support a program at Langley aimed at developing cryogenic tunnel technology in areas such as model construction, test techniques, control systems, and efficient operating procedures.[4,9,10,11] The results of some of the more recent studies in these areas are given in later sections of this paper.

3. SAFETY

From the earliest days of the 0.3-m TCT, beginning with the design of the tunnel, safety has been an ever present concern. The tunnel was designed and built to be used for no more than 60 hours of testing in order to verify the validity of the cryogenic wind tunnel concept at transonic speeds. The role of the 0.3-m TCT has obviously changed during the almost 12 years of operational experience. Rather than the 60 hours for which the tunnel was designed, as previously noted, we have accumulated over 5000 hours of operation, mostly at cryogenic temperatures and at absolute pressures ranging up to 6 bars.

Over the years, as a direct result of the changing research roles of the 0.3-m TCT, additions and modifications have been made to the physical equipment of the facility as well as to the procedures used in its operation. As a part of an ongoing program within the Experimental Techniques Branch designed to ensure that the existing equipment and operational procedures of the 0.3-m TCT facility are acceptable in terms of current standards of safety for cryogenic systems, two independent safety reviews have been made by outside consultants.[12,13]

As noted in Reference 13, the operation of the 0.3-m TCT involves the storage of liquid nitrogen received from an outside supplier, the transmission of liquid nitrogen to the tunnel by pump, and the exhaustion of the gaseous nitrogen from the tunnel to the atmosphere. In general these operations would be expected to lead to the potential exposure of personnel and equipment to the following hazards:

(1) Asphyxiation due to oxygen deficiency.
(2) Freezing of human tissue due to excessive cold.
(3) Failure of metal parts and materials which are not suitable for use at low temperatures.
(4) Overpressurization failures due to vaporization of trapped liquid nitrogen.
(5) Failures due to differential contraction and expansion.
(6) Fires and explosions caused by condensed atmospheric air coming in contact with combustible material.
(7) Fog formation and icing due to escape or intentional release of cold fluids.
(8) Exposure to excessive noise.
(9) Incorrect installation of cryogenic equipment.
(10) Inadequate training to alert personnel on hazards which are alien to normal experience.
(11) Inadequate provision of rescue equipment.

A brief description is presented in the following sections to indicate the approach taken at the 0.3-m TCT to avoid the hazards listed above.

3.1 Organization

Two very important concepts at Langley directly related to safety are "quality assurance" and "configuration control." Quality assurance may be loosely defined as a set of procedures that ensures that you are using what you think you are using, whether it be a complete model with critical design dimensions or a bolt which must be of a specific material produced in a prescribed manner. Configuration control is loosely defined as having records, such as a set of drawings, which reflect the true up-to-date situation with respect to the tunnel hardware, electrical wiring, plumbing, etc.

In the early days of operation of the Langley 0.3-m TCT, several safety-related incidents occurred which may have been caused by our inexperience combined with the lack of a proper quality assurance program and an organizational structure suitable for cryogenic wind tunnels. However, soon after the classification of the 0.3-m TCT was changed from a pilot tunnel to an operational wind tunnel facility, it was decided that all materials, models, and test equipment used in cryogenic tunnels at Langley would be "flight rated," a generic term which implies that there is a special concern with the overall operating environment, design criteria, safety factors, and quality assurance of the article.

As might be expected, the subsequent development of the U.S. National Transonic Facility (NTF) at Langley added momentum to these concerns and hastened the evolution of new quality assurance standards and review procedures for cryogenic testing. New positions of responsibility, such as "Cryogenic Practice Engineer," appeared in the organizational structure, and handbooks dealing specifically with cryogenic model criteria[14] and a quality assurance plan[15] were incorporated in the Langley Safety Manual.

The system which has evolved at Langley is obviously too complicated to be considered for every cryogenic wind tunnel. This is especially true where competent researchers are running their own small cryogenic tunnels and the results of an accident would not be catastrophic. Most small cryogenic tunnels operating at atmospheric pressure can be safely operated without any formal safety program. However, for the larger cryogenic tunnels, especially those that are pressurized, there are certain basic elements of a formal safety program which provide the necessary organizational structure for the safe and efficient operation of the cryogenic tunnel.

At Langley, it has been found that a Facility Safety Head (FSH) and a Facility Coordinator (FC) should be formally assigned to manage the day-to-day safety program. These two positions, described in Reference 15, provide the foundation for an acceptable safety program. The FSH is usually a research engineer, familiar with the operation of the cryogenic tunnel, who serves as the on-site manager of the safety program. The primary function of the FSH is to assess and control hazards and thereby minimize the possibility of an accident. The FC is normally the senior technician in charge of the tunnel operational team who assists the FSH in configuration management and the safe operation of the facility.

In addition to the FSH and the FC, the impartial "third party" within the organization is the Cryogenic Practice Engineer (CPE) with the responsibility of providing a constant check on approach of designs for baseline configuration changes, models, and test equipment. The CPE has an up-to-date collection of information on subjects related to the selection of materials, design, and fabrication techniques for cryogenic wind tunnel devices.

At Langley, any significant changes or additions to the original, "baseline," facility configuration is processed and supervised by a Technical Project Engineer (TPE) who is responsible for coordinating the effort with the FSH to insure that all facility drawings are corrected and operational procedures are updated if required.

Finally, each research project in the tunnel, such as an airfoil test, is sponsored and supervised by a Research Project Engineer (RPE) who has a thorough knowledge of the details of the individual research project and a basic familiarity with the major characteristics and safety concerns of the facility.

Prior to each test, a pre-test meeting is held with the FSH, the FC, and the RPE present to review the safety aspects of the proposed test, including a detailed review of the test equipment and procedures.

The key safety elements in this or any other pressurized cryogenic tunnel are:

(1) Define and document the original or "baseline" facility configuration.

(2) Validate the baseline facility configuration. Basically, this involves gradually extending the operation of the tunnel to the limits of its operating envelope.

(3) Control and document all changes to the baseline facility configuration.

(4) Operate the facility properly.

3.2 Operational Procedures

The development and maintenance of operational procedures and check sheets represents a continuing task at the 0.3-m TCT. After almost 12 years of operation, we are still updating and modifying our procedures and check sheets to reflect modifications to equipment or improvements in operating procedures.

The operational procedures establish a set procedure for all major recurring functions and tasks, such as system start-up, purging, cooldown, operation, warm up, operational limits, protective clothing, "buddy" system, communications, reoxygenation, tunnel entry, emergency reactions, low O_2 response, evacuation of facility, and system shutdown. The operational procedures also provide guidance to avoid hazards associated with restricted areas, low temperatures, low O_2 levels, high voltage sources, moving parts, O_2 enrichment, moisture in the tunnel, excessive fogging at the tunnel exhaust, rupture of the tunnel or nitrogen systems, and "puddling" of LN_2 in the tunnel.

Check sheets are used each time the 0.3-m TCT is being prepared for a test. The check sheets are arranged by system and provide both start-up, operational, and shut-down steps which are checked off by a qualified tunnel technician as they are performed. In the 0.3-m TCT, check sheets have been developed for tunnel operation, cooling water system, hydraulic system, tunnel control systems, fan drive shaft lubrication system, fan drive motor lubrication system, instrumentation, LN_2 system, and test section.

3.3 Training

Training is a vital part of any safety program. A proven and acceptable method for training and qualifying the tunnel technicians is to address the training by facility system categories identical to the categories used for the facility check sheets. For example, if a technician is qualified on the drive system, that technician is authorized to prepare the drive system for operation and "sign off" on the drive system start-up and shutdown check sheets. The FSH and the FC share responsibility for qualifying the technicians on the various facility and tunnel control systems.

It is essential that the operators of pressurized cryogenic tunnels be provided with training that leads to a good understanding of the interaction between the various tunnel control parameters. Such training and knowledge enable the technicians to control the tunnel properly and to respond quickly and properly to undesirable events such as LN_2 "puddling" in the tunnel circuit. Periodic meetings devoted to safety and briefings by visiting specialists as well as self-graded achievement tests have proven to be very helpful in training the operating personnel at the 0.3-m TCT.

In the safety program for the 0.3-m TCT, advantage is always taken of available resource material and information related to safety and cryogenic systems. References 16 and 17 are examples of sources of safety related information that are required reading for all tunnel operating personnel.

Training represents a key element in the safe operation of these relatively new and rather complex cryogenic wind tunnel facilities. As such, the training program should be periodically reviewed and updated as required to meet changing needs.

4. TEST RESULTS

As previously mentioned, a great variety of research has been conducted in the 0.3-m TCT during the past 11 years. Included in this research have been tests of conventional, peaky, and supercritical airfoils, side-wall boundary layer removal effects, non-adiabatic wall effects, and laser diagnostics. The results of many of these tests have been reported and are cited in the latest bibliography on cryogenic tunnels.[18] Other research has been conducted but not yet reported. In this category are studies of the flow field about a cylinder, flutter tests, tests of an oscillating airfoil, and tests to develop transition detection methods. These topics are too numerous to be

discussed here in any detail. Therefore, a few studies believed to be of more general interest have been selected to be discussed at some length.

4.1 Balance Studies

A test of an unheated European Cryogenic Strain Gage Balance was made in the 0.3-m TCT under a collaborative agreement on cryogenic transonic wind tunnel testing between NASA and the European Transonic Windtunnel (ETW) Countries under the auspices of the AGARD Fluid Dynamics Panel. The objectives of this test were:

(1) To obtain steady-state force and moment data at temperatures of 110 K and 200 K to compare with data taken at 300 K (ambient) in order to determine the performance and accuracy of the European strain gage balance.

(2) To measure the temperature response of the model, balance, and sting during normal and rapid changes in tunnel stream temperature.

The European balance has the designation NLR 771 and was designed and constructed specifically for testing at cryogenic temperatures by the staff of the National Aerospace Laboratory (NLR) in the Netherlands at the request of the Technical Group ETW.

The balance is 21.21 cm long and 2.54 cm in diameter. It is made from one piece of Vakumelt Ultrafort 301 maraging steel. It is a three-component balance with design loads as follows:

Normal force	=	890 N
Axial force	=	112 N
Pitching moment	=	28 N•m

As can be seen in the sketch of Figure 3, the balance has a forward and an aft bending-moment bridge. Outputs of the two bending-moment bridges are added and subtracted to produce voltages which are proportional to normal force and pitching moment. These bridges incorporate additional strain gages mounted in a direction perpendicular to that of the actual strain sensing gages to minimize temperature effects. The axial-force bridge does not incorporate these additional transverse gages.

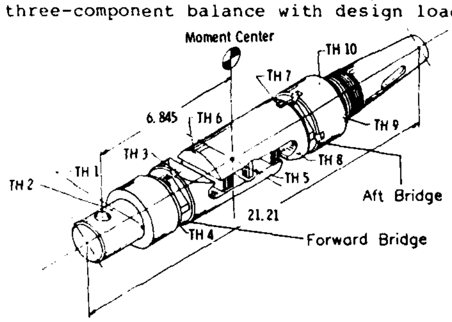

Fig. 3 Sketch of NLR 771. "TH" indicates thermocouple locations.

A tubular shield cantilevered forward over the gage section of a Langley balance had been found to improve the stability of the balance outputs at cryogenic temperatures in previous aerodynamic tests in the 0.3-m TCT. Such a shield tends to greatly reduce convective heat transfer and is therefore commonly referred to as a "convection shield." The NLR 771 balance was tested with and without a convection shield.

The delta-wing model of 75 degrees sweep, the sting, and the sting support hardware used in this test were the same as previously used to test Langley cryogenic strain gage balances as reported in Reference 19.

For this test, data were obtained through the regular data acquisition computer at the 0.3-m TCT for off-line computation at the central computer facility using both the NLR method of data reduction for force balances and the standard Langley method. The balance was recalibrated at Langley to obtain the coefficients necessary for the Langley data reduction method. In addition, a digital desktop computer system was used for on-line data acquisition and reduction.

Two types of runs were made in the 0.3-m TCT. Steady-state runs were made at constant temperature conditions during which force and moment data were acquired over a range of angle of attack. Figure 4 shows a comparison of data taken at 300 K, 200 K, and 110 K. The total pressure was varied to keep the Reynolds number constant. Good agreement is apparent for the normal force and the pitching moment data. The axial component is only lightly loaded with this model and the difference evident in the axial data is a result of balance sensitivity for a low-load condition with the usual one-half percent accuracy for a strain gage balance. Both the normal and the pitch components are loaded to a higher percentage of balance capacity than is the axial component.

The other type of runs were those in which the stream temperature was varied while the angle of attack, Mach number, and total pressure were held constant. Two different rates of varying the temperature were used to simulate requirements for use of a strain gage balance in a large cryogenic tunnel such as the NTF or the proposed ETW.

The first of these involved varying the stream temperature at a maximum rate of 10 kelvins per minute in order to stay within the operating requirements for the structure of the 0.3-m TCT. This is normally the maximum rate for changing temperature both for cooling down and for warming up the 0.3-m TCT.

The second type of transient temperature testing involved varying the temperature as rapidly as possible, but only over a maximum range of 50 kelvins, again limited in the

0.3-m TCT by thermal and structural constraints. Very rapid temperature changes such as this have been suggested for use in the NTF or the ETW as one way to conserve nitrogen during a change in test conditions.

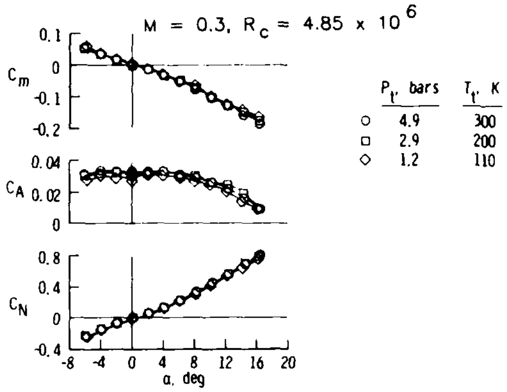

Fig. 4 Steady state data.

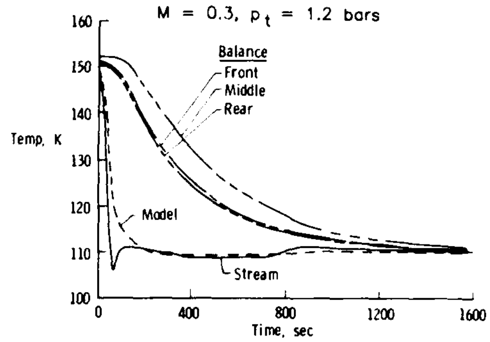

Fig. 5 Transient temperature data.

Figure 5 shows the result of a rapid change in stream temperature from 150 K to 110 K which took about 50 seconds. As can be seen, the model temperature follows the stream temperature reasonably closely, reaching a nominal 110 K in about 180 seconds. However, the balance temperatures take about 20 minutes to approach the stream temperature. The middle of the balance, where the axial section is located, is somewhat slower than either the front or the rear of the balance.

All of this strain gage balance data, which involved about 14,000 data points because of the long temperature response runs, was transmitted to the Technical Group ETW in October of 1984, and a detailed analysis of the data is under way.

4.2 Buffet Studies

Buffet tests were made on two semispan-wing models in the 0.3-m TCT over a range of stagnation temperatures and pressures.[20] This study was designed to determine if an existing buffet testing technique, the measurement of the unsteady wing-root bending moment, could be used successfully at cryogenic temperatures. Buffeting can be defined as the structural response of an aircraft or test model to the aerodynamic excitation produced by separated flows. Because buffeting is a separated flow phenomenon, it is, of course, dependent on Reynolds number. Cryogenic wind tunnels, which have the capability to vary Reynolds number over a wide range, present a unique opportunity for research in the area of buffet testing. The buffet tests described herein were based primarily on suggestions made by Mabey of the Royal Aircraft Establishment at Bedford, England.[21]

The evaluation of the buffet testing technique was done by obtaining comparable dynamic wing-root bending moment data at both ambient and cryogenic temperatures to validate the suitability of both the technique and the instrumentation. The secondary objectives were to utilize the unique capabilities of the cryogenic pressure tunnel to study the Reynolds number effect on buffeting at constant dynamic pressure and to study the effect of model aeroelastic distortion on buffeting at constant Reynolds number.

Two buffet semispan-wing models similar to those suggested by Mabey were constructed of aluminum alloy and instrumented for these tests. One model was a slender, sharp-leading-edge delta wing with 65 degrees sweep known to be relatively insensitive to variations in Reynolds number. This configuration was chosen to provide a base-line model to demonstrate the test technique over the temperature range in the cryogenic wind tunnel. The other model was an unswept wing of aspect ratio 1.5 with a British NPL 9510 airfoil section which was expected to be very sensitive to variations in Reynolds number. The semispan-wing models were cantilevered from a turntable located in the side wall of the two-dimensional test section of the 0.3-m TCT. Tests were made at subsonic Mach numbers over a range of stagnation pressure from 1.2 bars to about 5.9 bars and of stagnation temperature from 300 K to 100 K. The angle of attack was varied from -4° to $+32^\circ$ for the delta-wing model and from -2° to $+18^\circ$ for the NPL 9510 wing. Measurements were made of both the dynamic and the steady wing-root bending moments.

The results from the buffet tests of the delta wing model are shown in Figure 6. Data were obtained at the same free-stream velocity, V, which gave almost the equivalent reduced-frequency parameter, k, and the same dynamic pressure, q, by adjusting the Mach number, M, and the stagnation pressure, p_t. Any Mach number effect should be small at these low Mach numbers. Good agreement for the dynamic root bending moment, $C_{B,D}$, was obtained over the entire range of angle of attack using this procedure. This good agreement is considered to demonstrate that the the root bending-moment strain-gage technique operates satisfactorily at cryogenic temperatures. It should be pointed out that the variation in the reduced-frequency parameter, k, from 5.71 to 6.01 radians for

the ambient and the cryogenic data, respectively, is a result of the frequency of the first natural bending mode increasing with a decrease in temperature because of an increase in the modulus of elasticity of the aluminum alloy.

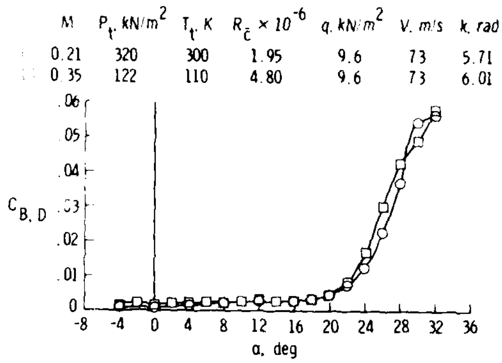

Fig. 6 Comparison of ambient and cryogenic buffet data for delta wing model.

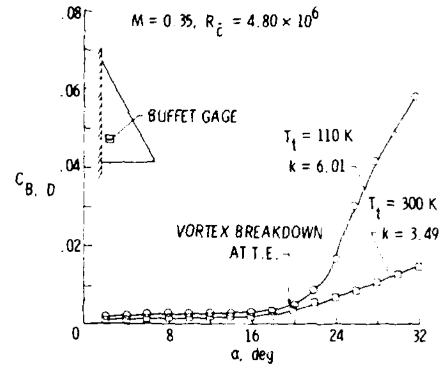

Fig. 7 Effect of reduced frequency on buffet response.

The unique capability of the cryogenic tunnel, in which control of the speed of sound can be utilized to provide a range of reduced frequencies while maintaining constant Mach and Reynolds numbers, is illustrated by the results presented in Figure 7. Data are shown for a Mach number of 0.35 and a constant Reynolds number for two values of the reduced-frequency parameter obtained by temperature variation. Also indicated is the angle of attack at which, from the study of Reference 22, vortex breakdown has reached the trailing edge. The buffet measurements indicate that the onset of buffet coincides with vortex breakdown at the trailing edge and that the intensity, which increases as the vortex breakdown moves toward the wing apex, is highly dependent upon the reduced frequency. At a given angle of attack beyond buffet onset, the buffet intensity is seen to increase greatly as the reduced-frequency parameter is increased from 3.49 to 6.01 radians. It has been suggested by Mabey,[23] based on the frequency spectrum of pressure measurements on a different slender-wing planform, that the large difference in the dynamic root bending moment after buffet onset is a result of the magnitude of the excitation spectrum increasing with the increase in reduced-frequency parameter associated with the difference in ambient and cryogenic temperatures. The leading-edge vortex type of flow on the two types of slender wings should be similar even though the detailed geometry of the planforms is different.

Further cryogenic wind tunnel buffet tests of the delta wing planform are contemplated. Mabey has suggested, as part of a NASA/RAE collaborative effort, that carbon-fiber reinforced epoxy would be an interesting material for cryogenic buffet test models. The ratio of the modulus of elasticity to the density of carbon-fiber reinforced epoxy is about four times larger than the similar ratio for aluminum and other typical metals. Thus, from beam theory, a model made out of carbon-fiber reinforced epoxy with the same thickness as an aluminum model would have a first natural bending frequency twice that of the aluminum model. This higher natural frequency will provide the opportunity to explore further the previously discussed effect of reduced-frequency parameter on the dynamic bending moment of the 65 degree sweep delta wing.

Two delta wing models made out of carbon-fiber reinforced epoxy are under construction. One is the same thickness (5 mm) as the original delta wing model and the other is half the thickness. The latter model will be used to provide baseline data to verify the carbon-fiber model data against the data from the aluminum model and the thicker model will provide data at about twice the reduced-frequency parameter of the aluminum model. These tests are planned for late 1985 and will be run in the new adaptive wall test section in the 0.3-m TCT.

4.3 Condensation Studies

As part of the overall program to develop transonic cryogenic wind tunnels, researchers at NASA Langley have been investigating the effects of onset of condensation in nitrogen gas.[24-29] It is important to know at what temperature condensation effects occur since the onset of condensation effects determines the minimum operating temperature (MOT) of cryogenic tunnels and, consequently, determines the maximum benefit to be gained by operating at cryogenic temperatures.

For example, if it is possible to operate without condensation effects at temperatures below those corresponding to saturation at the maximum local Mach number over the model, increases in Reynolds number from 10 to 30 percent are possible over what would be obtained at temperatures which avoid any saturation over the models. An example of the potential benefits of operating beyond the local saturation boundary is shown in Figure 8 where the saturation boundaries of interest are shown on the

well known curve of the variation of Reynolds number with temperature. As can be seen, for a given size tunnel and a constant operating pressure, a significant increase in Reynolds number is possible if the saturation boundary may be crossed in these localized, high Mach number regions.

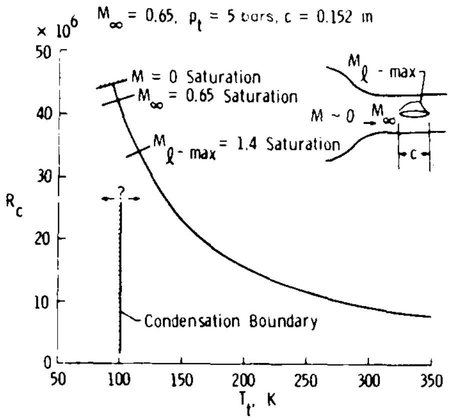

Fig. 8 Effect of reducing temperature on Reynolds number.

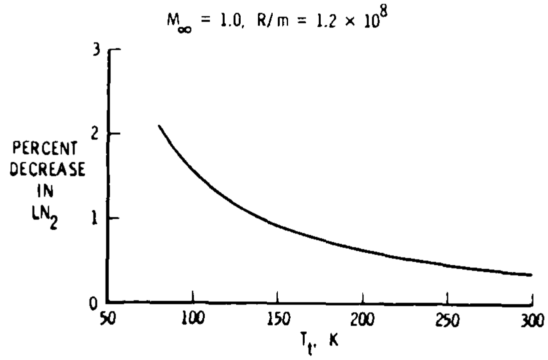

Fig. 9 Change in LN_2 consumption per 1 kelvin decrease in T_t.

In addition to increasing the maximum Reynolds number capability, MOTs below local saturation are important when determining the most cost-effective way to operate a cryogenic tunnel for a given value of Reynolds number. Since most cryogenic tunnels take advantage of both increasing tunnel pressure and decreasing tunnel temperature to increase Reynolds number capability, a lower tunnel temperature means less pressure is needed to achieve a given value of Reynolds number. As explained in more detail in Reference 27, direct on-point operating expenses can be minimized by operating at MOT. The reason for this decrease in operating cost with decrease in temperature is shown in Figure 9. As can be seen, for a given value of Reynolds number, the LN_2 consumption decreases about 2 percent per kelvin at the lower temperatures.

In Reference 29, Hall does an excellent job of summarizing the results from a series of experimental measurements of the onset of condensation for six different studies involving pressure-instrumented airfoils in the Langley 0.3-m TCT. The airfoils used in Hall's analysis include conventional (0.137-m NACA 0012-64, 0.152-m NACA 0012), peaky (0.152-m NPL 9510), and supercritical (0.152-m NASA 0712-3, and 0.152-m and 0.076-m versions of the CAST 10-2/DOA 2). The results from these experiments and a previous analysis by Sivier are then used to formulate a procedure for predicting minimum operating temperatures in the 0.3-m TCT.

In Figure 10, predictions from this procedure are used to illustrate typical increases in Reynolds number capability due to operating at the MOT as a function of total pressure. As can be seen, for values of free-stream Mach number greater than 0.45, increases in Reynolds number above that associated with operating at local saturation temperatures vary from about 7 to 22 percent, depending on pressure and both free-stream and local Mach number.

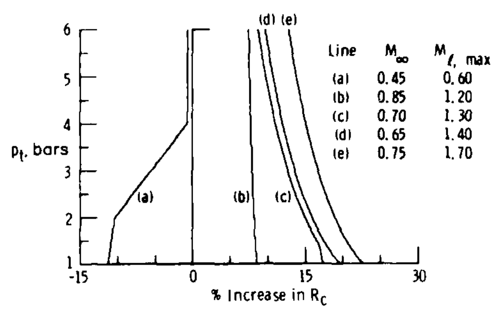

Fig. 10 Increase in Reynolds number due to operation at MOTs.

The unusual shape of curve (a) in Figure 10 is probably due to the fact that at the low fan power levels required for the lower values of Mach number, the liquid nitrogen injection system at the 0.3-m TCT in use at the time of these tests did not do a good job of atomizing the small amount of injected liquid into droplets and the relatively large droplets triggered effects in the pressure data similar to those that would be seen from actual condensation in the stream. It should be noted that since these data were taken, the LN_2 injection system for the 0.3-m TCT has been modified to permit complete closure of up to 3 of the 4 injection valves in order to ensure more efficient atomization of the LN_2 at the low flow rates required at the lower Mach numbers.

5. ADAPTIVE WALL TEST SECTION

5.1 Principal of Operation

Interference from the walls of the test section has historically been one of the major problems in wind tunnel testing, especially at transonic speeds where testing with solid walls may lead to the flow choking. The usual solution to the problem of choking is to use ventilated or porous walls in the test section. However, even ventilated walls can cause unwanted interference effects. Because of the complex nature of the flow associated with ventilated walls, corrections for wall interference effects are often difficult or impossible to calculate and apply.

If solid test section walls can be contoured to prevent choking, in theory they can also be contoured along streamlines or streamsurfaces to reduce or eliminate wall interference. In addition, compared to ventilated walls, solid walls should offer significant advantages by reducing the tunnel losses, thereby reducing the power required to drive the tunnel and reducing the noise level in the test section. Contouring the solid walls of the test section along free-air streamlines is the basis of the adaptive wall test section concept being pursued at the NASA Langley Research Center and at other research establishments including the University of Southampton, the Technical University of Berlin,[30] and, as you have heard earlier in this Special Course, at ONERA-CERT in Toulouse.

The following section of this paper will describe the NASA Langley 0.3-m TCT adaptive wall test section and the type of tests planned for the new test section.

5.2 Description of Adaptive Wall Test Section

5.2.1 Basic Design

The design of the adaptive wall test section for the 0.3-m TCT is based on the work done at the University of Southampton by Goodyer and his co-workers. This test section is basically configured for two dimensional testing.

The test section is 33 by 33 cm in cross section at the entrance and is 142 cm long. All four walls are solid with the top and bottom walls being flexible and movable. The flexible walls are 182 cm long and are fixed at the upstream end of the test section. The downstream 40 cm portion of the flexible walls provides a smooth transition between the end of the test section and the beginning of the fixed diffuser. The downstream ends are fixed vertically but are free to translate longitudinally as the wall shape changes.

The features of this test section are very similar to those of the two-dimensional test section briefly described in a previous section of this paper and reported in Reference 31. The model is supported between two turntables centered 78 cm downstream from the entrance of the test section. Models with chords up to 33 cm can be tested over an angle-of-attack range of ±20 degrees. Windows in the top portion of the turntable allow limited viewing of the region above the model.

A vertical traversing mechanism can be installed at either 32 cm, 44 cm, or 57 cm downstream of the center of the turntable. The maximum travel of the traversing mechanism is 25 cm. Porous plates for an optional sidewall boundary layer removal system are centered 36 cm upstream of the center of the turntable. These plates are 18 cm wide and 38 cm tall and have a porosity of 10 percent.

5.2.2 Wall Positioning System

There are 21 positioning jacks on each of the flexible walls. The jacks are spaced so as to provide the finest wall shape control in the vicinity of the model. A stepper motor drives a 10:1 reduction gearbox to turn each jackscrew which can be extended 7.5 cm in the direction of positive lift and 2.5 cm in the opposite direction. Each jackscrew drives a block with two drive rods. The drive rods extend through seals in the tunnel pressure shell and are connected to a flexible plate which in turn is fixed to the flexible wall. This arrangement keeps the motor and gearbox accessible and out of the cryogenic environment. This type of attachment accommodates both linear and angular misalignment between the drive rods and the wall attachment fitting which is produced when the wall is deformed from a straight line shape.

5.3 Instrumentation

The wall position is measured by a linear variable displacement transducer (LVDT) located outside the pressure shell. The transducer measures the position of the drive block which can be directly related to the wall position. The transducer output is an analog signal which is linear over most of the displacement range.

Pressure taps are located along the centerline of the flexible walls at each jack station. In addition, there are pressure taps on the top and bottom walls at the entrance of the test section, on the lower surface of the contraction section, and on the upper surface of the diffuser. The pressures on each wall are multiplexed to an auto-ranging, capacitive-type pressure transducer having an accuracy of ±0.25 percent of reading. The autoranging capability is needed to obtain accurate data over the wide range of operating pressure without having to change range on the analog data acquisition system.

Details of how the various calculations are made and how the walls are positioned to conform to free-air streamlines are beyond the scope of this paper. Such details may be found in Reference 32.

5.4 Adaptive Wall Tests

The first "test" in the adaptive wall test section will be a tunnel calibration. The Mach number distribution along the centerline of each of the four walls of the test section will be measured along with the distribution on one of the turntables. The turbulence in the test section will be surveyed with hot film probes. The tunnel performance (power required for a given set of test conditions) will also be determined. During this first test, the wall shape required to maintain a constant Mach number through the test section will be determined with the adaptation software. These wall shapes are considered to be the displacements equivalent to an aerodynamically straight wall as opposed to a geometrically straight wall.

Upon completion of the initial check out of the adaptive wall test section, two airfoil tests are scheduled to determine the operational capabilities of the adaptation software and to investigate two-dimensional wind tunnel wall interference at high Reynolds numbers. Two NACA 0012 airfoil models, one with a 16.5 cm chord and the other with a 33 cm chord, will be tested to assess the software at values of tunnel height to model chord down to 1.0. The results from these tests can be compared with results from previous tests of the NACA 0012 in the 0.3-m TCT and other facilities.

Two cooperative programs, one a NASA/ONERA/DFVLR effort and the other a NASA/NAE effort, have been established to test CAST 10-2/DOA 2 airfoil models, one with a 22.9 cm chord and the other with an 18 cm chord. The data from these tests will be used to assess the effects of model manufacturing differences and to compare the results on the same airfoil model in different facilities.

The 22.9 cm model will be tested in the NAE High Reynolds Number 15 in. x 60 in. Two Dimensional Test Facility. These tests will be conducted at a tunnel height to model chord ratio of 6.66 and the results should be free of interference effects from the top and bottom walls. These interference free data will be compared with the results from the 0.3-m TCT. The 18 cm model will be tested at ONERA T-2 tunnel and the 0.3-m TCT. The comparison should be very interesting since each of the adaptive wall tunnels has different geometric characteristics and different adaptation algorithms.

As previously mentioned, cryogenic wind tunnels, which have the capability to vary Reynolds number over a wide range, present a unique opportunity for research in the area of buffet testing. The two delta-wing buffet models made out of carbon-fiber reinforced epoxy described in section 4.2 are to be tested in the adaptive wall test section. The models will be mounted on one of the turntables to vary the angle of attack. Once the buffet studies are complete, the models will then be used to study the problems associated with testing three dimensional models in a wind tunnel with only the top and bottom walls adaptable.

A major long term goal of the adaptive wall research is to develop a technique to test three-dimensional models at transonic speeds where most, if not all, of the wall interference effects are eliminated at the source by the proper choice of wall shape. Coupled with this is the need to determine the residual interference effects and to use analytical methods to reduce them to negligible levels.

6. FUTURE PLANS

6.1 Tunnel Modifications

The 0.3-m TCT with the new adaptive wall test section should have better flow quality than the 20 x 60 cm test section because of an increase in the contraction ratio from 9.4:1 to 10.7:1, decreasing the angle of the high-speed diffuser, and the elimination of the slotted test section walls. Other modifications to the tunnel are planned to further improve the flow quality. These planned modifications include replacing a section of the stagnation region with a rapid diffuser and new contraction section to increase the contraction ratio from 10.7:1 to about 15:1 and the addition of a variable second minimum downstream of the test section. It is anticipated that a sting type model support system for three dimensional testing will also be added. The preliminary engineering report for the contraction section and model support system has been completed. The final design is expected later this year with construction in 1986.

6.2 LN_2 Supply System

Several modifications to the LN_2 supply system are planned that are intended to make it safer and more efficient. Presently, LN_2 is delivered to the 0.3-m TCT site in large tank trucks which must back down a relatively narrow roadway in order to make connection to the off-loading station. In order to completely eliminate the off-loading operation, with its inherent danger and potential for contamination of the LN_2, a new supply line for the LN_2 storage tanks used for the 0.3-m TCT will be connected directly to the existing NTF supply line running from the local LN_2 plant to the on-site NTF storage tank.

Plans are also being made to completely redesign the LN_2 plumbing at the 0.3-m TCT to incorporate vacuum insulated lines and remotely operated control valves. An automatic sequencer/controller will be used in conjunction with the new plumbing for start-up, operation, and shutdown of the LN_2 system. The new LN_2 supply system will offer distinct advantages over the existing system with respect to both safety and efficiency. For example, the automatic remote operation of the LN_2 system will eliminate manual operation of the system which presently requires two technicians to be outside the tunnel building regardless of the weather. As with some existing systems, color television will be used to provide a general view of the LN_2 storage and pump area, providing additional information beyond that normally provided by temperature and pressure sensors. Such visual contact has proven to be very valuable, especially in areas where the venting of LN_2 or GN_2 can cause fogging.

7. CONCLUDING REMARKS

The Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) can operate from ambient to cryogenic temperatures at absolute pressures from about 1 to 6 bars. Since the 0.3-m TCT began operation in 1973, it has been used extensively in the development of instrumentation and operating techniques for cryogenic tunnels as well as for aerodynamic tests where advantage can be taken of the extremely wide range of Reynolds number available.

This paper has described the present capabilities of the 0.3-m TCT and given an overview of recent research activities which include both steady and unsteady testing. Emphasis in this paper has been given to safety and to the development of testing techniques for cryogenic tunnels. Results of studies aimed at establishing the lower limits of operating temperature have been presented and the impact of these studies on tunnel operation have been discussed. Finally, some of the design features and operating characteristics of a new self-streamlining wall test section recently installed in the tunnel circuit were described.

Based on over 5000 hours of operation of the 0.3-m TCT, it is concluded that practically any type of research that can be done in an ambient temperature tunnel can also be done safely in a cryogenic wind tunnel. The outstanding difference is that the cryogenic tunnel offers the researcher values of test Reynolds number at or near full scale values while opening up several new research possibilities due to the independent control of pressure, temperature, and Mach number.

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9. ACKNOWLEDGMENTS

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THE U.S. NATIONAL TRANSONIC FACILITY - I

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Summary

The construction of the National Transonic Facility was completed in September 1982, and checkout operations started the following month, with the maximum Reynolds number being obtained in May 1983. Following, most of the effort was devoted to installing the model access housings, and adjusting or altering various tunnel hardware systems. In May 1984, preliminary aerodynamic calibration of the tunnel was initiated in parallel with checkout of the tunnel operating systems, and in August 1984, the tunnel was declared operational and turned over to the user organization for a complete aerodynamic calibration and research and development testing. The facility has been operated in both the air and nitrogen modes covering a Mach number range of 0.2 to 1.22 at pressures up to 8.5 atm and at temperatures down to 100K. This paper presents a status of the tunnel operating systems and an overview of the major milestones during checkout.

Introduction

Final design and construction of the National Transonic Facility (NTF), located at the NASA Langley Research Center, a cryogenic wind tunnel designed to meet the United States' need for high Reynolds number testing, was formally initiated in July 1975. Nine years later, in August 1984, the operational readiness review was completed, and the facility was declared operational for aerodynamic research and development testing to commence.

The history of the NTF and description of the design characteristics are well documented in references 1 through 11. The preliminary aerodynamic performance results are documented in reference 12. This paper presents a status report on the tunnel operating systems and an overview of the time required to perform the major events of the checkout plan. A brief description of the facility and its unique aspects is included.

Facility Description

An aerial view of the NTF site, viewed from the back side, is presented in figure 1. The large bulk storage nitrogen tank on the left and the vent stack at the right of the tunnel are used to support the cryogenic mode of operation. The cooling tower in the foreground is used with a water-cooled heat exchanger inside the tunnel to support the air mode of operation. The high bay building in the background houses model preparation bays and shop area on the first floor and the control room and tunnel test section entrance on the second floor. The design performance capability is a Mach number range of 0.2 to 1.2, pressure range of 1 to 8.8 atm, and temperature range of 77 to 339K. This will produce a ma[illegible] Reynolds number of 120 million at a Mach number of 1.0 based on a chord length [illegible] meters.

The majority of the nitrogen is supplied to the on site 946 cubic meter storage tank by pipeline from a commercial air separation plant as shown in figure 2. This system has been operational since January 1983 and supplied most of the liquid nitrogen for the NTF during checkout. The on site storage tank can also be filled from mobile truck units.

The aerodynamic lines of the tunnel are shown in figure 3. The overall dimensions are 61 meters between centerlines in the long direction and 14.6 meters between centerlines in the short direction. A 15:1 contraction ratio is employed ahead of a slotted test section (six slots each in the floor and ceiling and provisions for two slots in each sidewall). A photograph of the test section showing some of the key features is presented in figure 4. For cryogenic operations, nitrogen is vaporized into the circuit in the short leg ahead of the fan and vented at the opposite end. A photograph showing LN_2 spray nozzles on the two lower arms of a cruciform spray bar arrangement is presented in figure 5.

One of the major features of the NTF is the internal thermal insulation system which maintains the pressure shell at near ambient temperature during cryogenic operation. This system, illustrated in figure 6, consists of a closed-cell foam material bonded to the inside of the pressure shell. The total thickness is approximately 18cm. In the low speed legs of the tunnel, an aluminum liner covers the insulation for protection and provides the flow surface. A view of the low speed diffuser showing the liner panels installed is shown in figure 7. The panels

are approximately 60 by 90cm and are free to expand or contract as required by thermal changes. The fan nacelle tail cone is also visible in this figure. Geometric details of the fan region are shown in figure 8. The upstream fan nacelle is bent through the turning vanes of corner 2. The fan itself is a single-stage fan with 25 fixed-pitch blades that are fabricated of fiberglass-reinforced plastic. The fan loading is changed by variable inlet guide vanes, 24 in number, or by variable rotational speed. There are 26 fixed-pitch outlet stator blades downstream of the fan.

Although the high Reynolds number operation utilizes nitrogen as a test gas, provision for operation in air at ambient temperatures has been made. In the air mode of operation, the heat of compression from the fan system is removed by a water-cooled heat exchanger. The heat exchanger is a finned-tube design and is located at the exit of the wide-angle diffuser at the upstream end of the settling chamber - see figure 3.

The control room is large and fully equipped. Tunnel control functions are performed at one end of the room (figure 9) with data acquisition and processing performed at the other end (figure 10). The data system is built around four 16 bit mini-computers with a total memory of 3 megabytes, individual hard disk drives, and other associated peripherals. The separate systems are dedicated to data management, data acquisition, process control, and process monitoring. Load sharing capability is provided to the point that the tunnel can operate safely in a reduced capability mode, using only two of the four computers. On-line data for test monitoring is available on cathode ray tube displays with hard copy capability. Flatbed plotting capability is also available for on site final plotting of data. System software for tunnel operation and calibration has been checked out. Applications software routines for model data acquisition and manipulation have been developed and those required to support the checkout, aerodynamic calibration, and initial test programs of the facility have been verified.

The first floor of the NTF shop area is dedicated to model preparation. Three model buildup rooms are located across the front of the building with a shop area for light mechanical work occupying the remainder of the space. Each model room is equipped for model buildup and checkout. A model support backstop capable of pitch, roll, and vertical motions is shown in figure 11. The sting connection on this model support backstop is identical to that in the test section. A junction box with plug terminals to the data acquisition system is located in the rear of each room. A dead weight calibration system with a hydraulic lifter is located in the basement beneath the model rooms. A portable cryogenic chamber, as illustrated in figure 12, is available. With this system, models will be assembled on the sting as they are to be installed in the tunnel, cryogenically cycled, and statically loaded under cryogenic conditions prior to tunnel entry.

To provide for a highly productive tunnel in a cost effective manner, access to the test section region of the tunnel, when in the cryogenic mode of operation, was a primary consideration in the design of the NTF. In as much as cooldown and warmup of the tunnel internals is time-consuming (approximately 8 hours per cycle) and uses large amounts of energy in the form of nitrogen and electrical power, two methods of gaining access to the test region have been provided as indicated in the flow diagram of figure 13. Upon completing a test run, the plenum isolation system is activated (see figure 14). Isolation valves upstream and downstream of the test section are used to isolate the test section region to permit access with the remainder of the circuit at elevated pressure and cryogenic temperature. To close the gate valves, vent the plenum to atmospheric pressure, and prepare the test section region for the next event takes about 30 minutes. If the model access mode is selected, access housings or tubes are inserted from either side of the tunnel (see figure 15). These housings seal at the tunnel centerline and after suitable conditioning of the housing environment and model surface have been completed, the housing doors are opened and work may be performed on the model under shirt sleeve conditions, see figures 16 and 17. The model access cycle, excluding model work takes about 2 hours. If the plenum access mode is selected, the plenum is purged and warmed using dry air until suitable working conditions are obtained. This mode is required for model installation and removal, or for access to model data systems located outside of the test section region.

<u>Tunnel Systems Checkout</u>

Construction was completed in September 1982, and the tunnel was first operated in the air mode on October 1 of that year. Following a successful checkout of all non-cryogenic systems, liquid nitrogen was introduced in the tunnel, and the internal structure was cooled to 120K on February 7, 1983. After two cooldowns and structural inspections, the tunnel was operated over the Mach number range with the pressure gradually increased on succeeding test runs. In May 1983 an operating condition of 117 million Reynolds number was obtained at a Mach number of 1, a pressure of 8.5 atm, and temperature of 119K. A summary of the operational experience of the tunnel systems follows.

In the air mode of operation, the water-cooled heat exchanger was operated slightly above its thermal design point. Approximately 40 megawatts of power was removed. The temperature uniformity of the discharge air over the coil is controlled by setting the cooling water flow in each of 36 heat exchangers (two counterflow heat exchangers per tube bundle). Balancing of the cooling water flow was performed during the preliminary aerodynamic calibration with the test section survey rake available to serve as a guide for temperature uniformity. Resulting performance results are discussed in Part II (reference 12).

The initial cooldown of the tunnel circuit in the nitrogen mode was made at a slow rate and then increased to the maximum rate of 0.75K per minute. Part of a typical temperature cycle is presented in figure 18. It will be noted that the initial stream temperature at the beginning of the figure was 225K. At the cooldown rate of 0.75K per minute, the stream temperature leads the flow side of the structure by about 25K with a temperature difference across the structure of about 30K. The total cycle took about eight hours with only a few minutes being consumed at the operating temperature of 117K for this case. The maximum cooldown and warmup rate established from this test, based on structural loading constraints due to thermal stresses, indicated reasonable agreement with that predicted during the design using an analytical model of the structure.

The internal thermal insulation system was given much attention during shakedown. During initial operation, some surface cracks occurred in the insulation. These were believed to result from stresses due to thermal gradients. The cracks were cleaned and filled with the same adhesive material which was used to bond the insulation to the shell, and tunnel operation was continued. These cracks have not reappeared. When operating in the cryogenic mode and after cold soaking overnight, frost spots occurred on the external surface of the shell over each attachment lug or link used to secure the insulation system to the shell (see figure 6). The lugs formed a small thermal leak path, as expected, and although local frost spots occurred, the majority of the shell surface was not similarly affected. The overall insulation system design criteria was to limit heat leakage to 300 Btu per second (316kW) over approximately 3,900 square meters of insulation at the cold operating condition. Preliminary data obtained during shakedown indicate that the insulation system is satisfying design objectives.

The electrical drive system for the fan has been operated at 124,000 fan shaft horsepower (92.5mW) for a short period of time. There were no unusual conditions observed or reasons to question longer runs. Also, the liquid nitrogen system was operated at the condition to offset this maximum power input to the tunnel stream by the fan. The maximum nitrogen flow rate was about 35 kiloliters per minute ($0.58 m^3/s$), and all components of the system operated as expected.

The automatic (closed loop) control of pressure, Mach number (fan speed and/or inlet guide vane position), and temperature have been operated in a stable condition, and acceptable performance has been demonstrated. The model pitch and roll control systems have been functionally checked and operated.

The test section configuration controls (test section walls, re-entry flaps, and model support walls) have been operated over their range and control has been demonstrated. These controls are slow response type compared to the process controls.

Effort to date has been devoted primarily to obtaining closed-loop control. During tunnel checkout and calibration, each control system was operated by manually inputing the setpoint to each system which was operating in the automatic mode to control either the tunnel process such as Mach number or the control element such as fan speed and/or inlet guide vane position. Future effort will be devoted to obtaining specific data to verify control laws and to placing in operation the test direction program to provide optimal controls from an energy efficient standpoint.

The safe venting of the gaseous nitrogen to the atmosphere was closely monitored during all cryogenic test runs. The system utilized is illustrated in figure 19. It employs a fan/ejector system which mixes ambient air with the gaseous nitrogen expelled from the tunnel in a vent stack 37 meters high. The mixing ratio in the stack is at least one-to-one under all conditions so that the oxygen content at the stack exit is at least ten percent by volume. The temperature is still low at the exit so that the size of the visible plume emitted is dependent on the atmospheric humidity and wind conditions. A photograph of the plume for a typical condition encountered at a Mach number of 1.0 is shown in figure 20. This one is at an operating pressure of 8.5 atm and temperature of 119K with a relative humidity of 40 percent. In this case, the plume dissipated very quickly. Comparison of this run and several others with the results predicted by an initial analytical model indicates agreement within 20 percent for the plume trajectory. Agreement for the horizontal dispersion distance is within 50 percent. The weather, tunnel operating conditions, and plume characteristics are recorded during many of the tunnel runs in the nitrogen mode in order to obtain sufficient data for updating the analytical model.

Checkout Schedule

The development of the detailed checkout plan for the NTF was started in early 1981. Considerable effort was devoted to reviewing the as-installed condition of all subsystems or components with regards to what tests had been performed and what was still required to verify operating performance. The Langley Research Center NTF project team performed as the prime contractor during construction for the various subsystems or components that were procured and installed by many contractors. The project team combined, procedurally, these subsystems and components into systems for checkout and startup of the facility. The functional checkout of these systems was the first part of the checkout plan. This provided for such items as electrical continuity checks, calibration of instruments and safety devices, and hardware operational checks. The systems were then integrated together for the second and third parts of the plan, that of operating the tunnel in the air and nitrogen modes, respectively. The latter two parts covered the facility operating envelope to verify that design objectives and overall tunnel performance criteria were obtained. Figure 21 shows the key milestones and the actual schedule when the major parts of the checkout plan were accomplished.

In January 1982, an integrated systems review (ISR) was conducted to assure readiness to commence the NTF checkout following construction. Around June 1982, the facility construction external to the tunnel circuit was completed, thus permitting effective checkout of the systems to start. On the inside of the tunnel circuit, the installation of the thermal insulation system and cleanup was completed in September 1982. The following month, the checkout of the NTF in the air mode of operation started and was completed in four months. In February 1983, the checkout in the cryogenic mode of operations started and in four months the maximum test point was achieved. Obtaining this maximum point in May 1983 with all tunnel systems performing satisfactorily was the most impressive milestone throughout the NTF checkout. For the first year of checkout, there were no major problems encountered, however, there were many challenges along the way which required system or component repairs, alterations, or modifications in order to obtain satisfactory performance.

In June 1983, the facility was shut down for three months while the model access housings or tubes were installed and fitted to the tunnel - see figure 15. During this time, various tunnel inspections and repairs were performed.

After returning to operation in September 1983, the primary effort was to check out the plenum isolation system - see figures 14 and 15. This is a very complex system with many large moving components. Electrical actuators are used to move these components, and they are located inside the tunnel and housed in heated enclosures. Many limit switches are mounted at strategic points inside the tunnel to define location of moving components and are exposed to the cold environment. Guide rails or tracks, exposed to cold environment, are used in positioning components to various locations. During the cryogenic checkout test in September, many problem areas were identified involving these components, and the tunnel was shut down for approximately two months for various alterations to the isolation system components. Such items as the heating system in the thermal enclosures for the actuators were modified in order to get enough heat into the proper components to keep the lubricating oil or grease warm and permit the unit to work; limit switch assemblies were redesigned to allow for greater thermal movement of the components; the chain drive systems inside the plenum doors were modified to allow for extra thermal growth; modifications to the overall door drive and locking mechanism had to be made to provide for more reliable operation; corrections had to be made for the guide rails or tracks which warped at low temperature causing binding of the moving components. The checkout testing resumed in November 1983, and the remaining tests were primarily associated with this plenum isolation and model access system.

The plenum isolation and model access system operated perfectly at ambient temperature, however, at cryogenic temperatures, the system or a part of it only operated partially or not at all. Not being able to inspect and see what was wrong at cryogenic temperatures and then losing the clue as to what was wrong when the tunnel warmed up, whereby it could be inspected, presented somewhat of a mystical challenge. However, by a review of the operating sequence logic, instrumentation, and from hardware post run inspection and analysis, the appropriate problems were identified and corrective action taken. To verify that the modifications or fixes had provided the appropriate corrective action, additional cryogenic tests were required. Several test cycles had to be performed, and some problems were not revealed until after others had been corrected.

In December 1983, the NTF dedication ceremony was held with the the Vice-President of the USA being the principal speaker.

In January 1984, a decision was made to shut down and perform a design modification for a problem that had been occurring over the previous months. The problem was the results of insufficient clearance between the fan drive shaft and the tunnel shell pressure seal - see figure 8 for general location. The tunnel

shell movement radial to the drive shaft was more than expected, and on one test run, the rotating shaft contacted the fixed portion of the shell seal. The correction, which decoupled the seal from the tunnel shell, was a major modification. Portions of the fan drive line components had to be disassembled, which required removing the large couplings and thrust bearing. Designing the new configuration, procuring new components, disassembling drive line components, and relocating and installing new equipment was all performed in three months; this was accomplished on a two work shift basis resulting in minimum tunnel down time and corrected the problem.

In May 1984, the tunnel returned to service, and preliminary aerodynamic calibration was started and performed in parallel with the plenum isolation/model access checkout. Parallel operation was performed to make the most efficient and effective use of the facility since the tunnel circuit was operating in a satisfactory manner.

In August 1984, the tunnel was declared operational.

Concluding Remarks

The construction of the National Transonic Facility was completed in September 1982, and checkout operations started the following month with the maximum Reynolds number being obtained in May 1983. Then effort was primarily devoted to installing the model access housings and adjusting or altering various tunnel components. In May 1984, the aerodynamic calibration started and was performed in parallel with checkout of the tunnel operating systems. In August 1984, the facility was declared operationally ready for complete calibration and aerodynamic research and development testing.

The facility has been operated in both air and nitrogen modes covering a Mach number range of 0.2 to 1.22 at pressures up to 8.5 atm and at temperatures down to 100K.

This paper presents the status of the tunnel operating systems resulting from the checkout and gives an overview of the major milestones during checkout.

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I wish to express my appreciation to NASA for permission to present this lecture and to thank others at the Langley Research Center whose willing assistance has made this lecture possible.

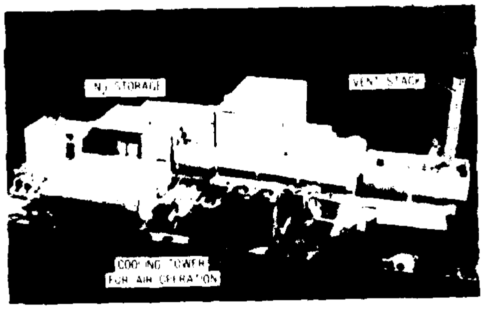

Figure 1.- National Transonic Facility.

Figure 4.- View of test section looking downstream.

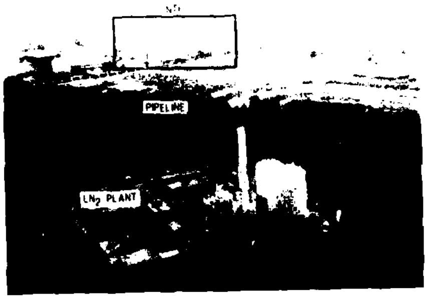

Figure 2.- View of liquid nitrogen production plant showing the NTF supply pipeline.

Figure 5.- Liquid nitrogen spray bars, view looking upstream.

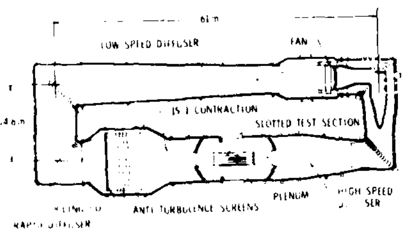

Figure 3.- Planview of the NTF circuit.

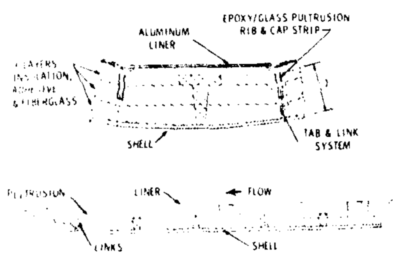

Figure 6.- Thermal insulation and liner system.

Figure 7.- Low speed diffuser, view looking upstream.

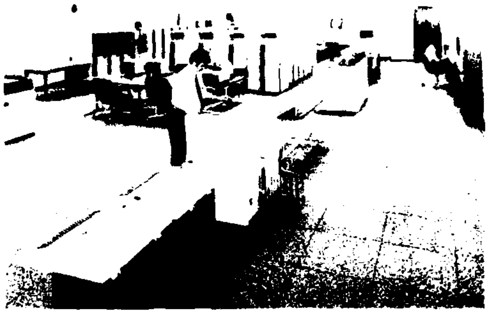

Figure 10.- NTF control room showing data acquisition and process monitoring equipment.

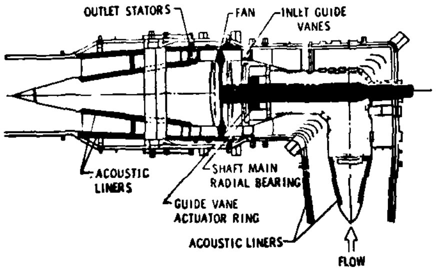

Figure 8.- NTF fan section assembly.

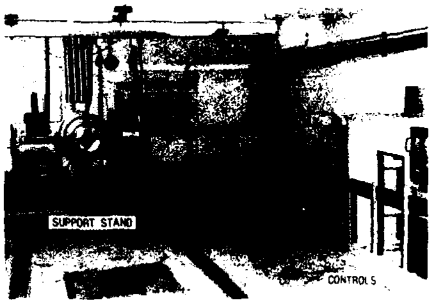

Figure 11.- Model check-out equipment installed in set-up rooms.

Figure 9.- NTF control room showing tunnel control consoles.

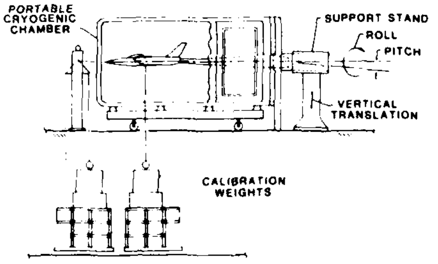

Figure 12.- Sketch of model check-out equipment showing portable cryogenic chamber.

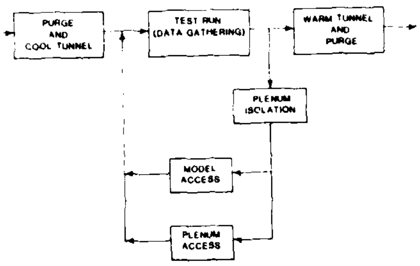

Figure 13.- NTF operating flowchart showing model and plenum access options.

Figure 17.- Closeup view showing model and interface seal joint between accessing housings.

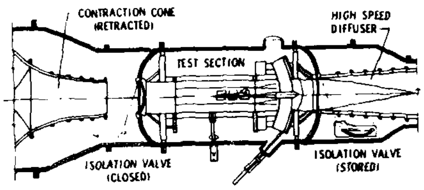

Figure 14.- NTF plenum/test section isolation system.

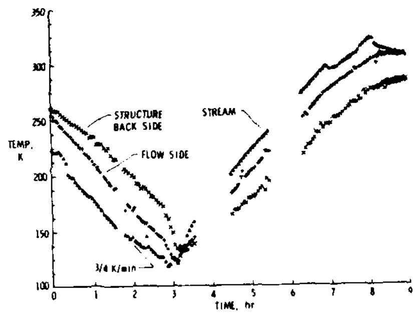

Figure 18.- Typical NTF operating temperature profile.

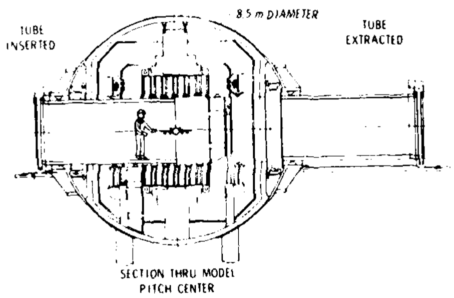

Figure 15.- NTF model access system.

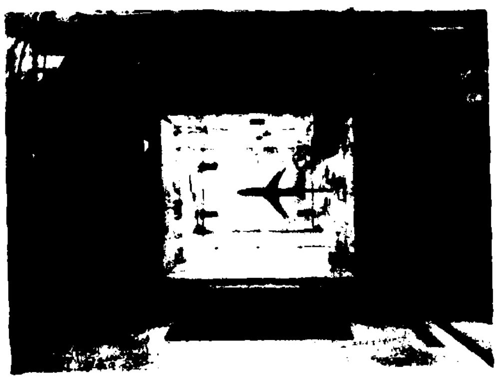

Figure 16.- Model access housings inserted into tunnel permitting work on model.

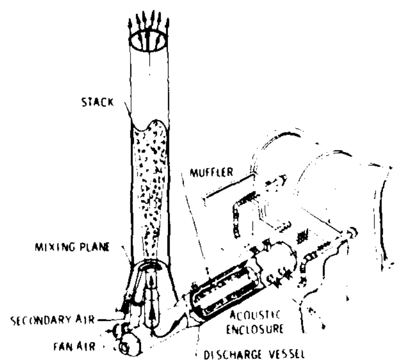

Figure 19.- Gaseous nitrogen vent system for the NTF.

Figure 20.- NTF gaseous nitrogen vent plume at $M = 1.0$, $P_T = 8.5$ atm., $T_T = 119°K$ and atmospheric relative humidity = 40%

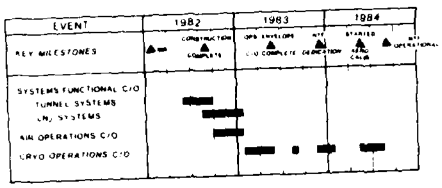

Figure 21.- NTF checkout schedule showing key milestones and when the major parts of the checkout plan were actually accomplished.

THE U.S. NATIONAL TRANSONIC FACILITY - II

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Summary

The construction of the National Transonic Facility was completed in September 1982, and checkout operations started the following month with the maximum Reynolds number being obtained in May 1983. Afterwards, effort was primarily devoted to installing the model access housings and adjusting or altering various tunnel hardware systems. In May 1984, the aerodynamic calibration started and was performed in parallel with checkout of the tunnel systems. In August 1984, the final operational readiness review was conducted and the facility declared operational for research testing.

The facility has been operated in both air and nitrogen modes covering a Mach number range of 0.2 to 1.22 at pressures up to 8.5 atm and at temperatures down to 100K. A limited amount of tunnel circuit performance information has been obtained and is presented in this paper.

An aerodynamic calibration plan has been outlined, and the first part of the steady-state calibration has been completed, of which some results are presented in this paper.

The first aerodynamic vehicle, Pathfinder I, was installed in December 1984 for checkout of instrumentation systems, and a status report and some results are presented.

Symbols

C_N	normal force coefficient
GN_2	gaseous nitrogen
H	test section width or height (2.5 meters)
K	Kelvin
LN_2	liquid nitrogen
M	Mach number
M_L	local Mach number
P	static pressure
$\tilde{P}$	root mean square (rms) value of fluctuating component of static pressure
P_{REF}	stagnation pressure in settling chamber
P_T	total pressure
R	Reynolds number
r	radial distance from centerline of tunnel
$R_{\bar{c}}$	Reynolds number based on $\bar{c}$ = .249m
t/c	thickness to chord ratio
T_{REF}	stagnation temperature in settling chamber
T_T	total temperature
T_T	rms value of fluctuating component of total temperature
U, V, W	streamwise, lateral and vertical velocities, respectively
U, V, W	rms value of fluctuating component of U, V, W
$\tilde{\rho}$	rms value of fluctuating component of gas density

Introduction

The National Transonic Facility (NTF) is a cryogenic wind tunnel designed to meet the United States' needs for high Reynolds number testing. Final design and construction at the NTF, which is located at the NASA Langley Research Center, was formally initiated in July 1975. Nine years later, in August 1984, the operational readiness review was completed; the facility was declared operational and turned over to the user organization for aerodynamic research and development testing to commence.

The history of the NTF, description of the design characteristics, and a status report on the facility hardware performance during shakedown operation are well documented[1-12]. This paper presents the preliminary performance results from the calibration of the tunnel circuit, test medium uniformity, and the status and some data from the first aerodynamic model, the Pathfinder I.

Tunnel Circuit Performance Results

Performance information has been obtained during shakedown and calibration including data on the tunnel pressure ratio and power consumption. Temperature and pressure data were measured at several stations in the tunnel. In particular, as shown in figure 1, measurements were made at the heat exchanger and the screens in the settling chamber, in the movable and fixed contraction, test section, high speed diffuser, and in the fan region. The subsequent discussion will concentrate primarily on the results of the measurements in the fan region. The types and locations of instrumentation in the fan region are shown in figure 2.

The pressure data from the total pressure rakes upstream and downstream of the fan system shown in figure 2 were used to determine the tunnel pressure ratio. The variation of pressure ratio with test section Mach number is shown in figure 3 for the NTF without a model installed. In air, the tunnel was operated at a temperature of about 320K and at pressures up to 3.7 atm. In nitrogen, the tunnel operation covered a complete range of temperatures from ambient to cryogenic, and pressures up to 8.5 atm. The data shown in figure 3 are representative of what was obtained at all test conditions.

Most of the published descriptions of the NTF have included some description of the expected performance of the wind tunnel. The most complete presentation of predicted NTF performance was given by Gloss and Nystrom[13] who showed the estimated pressure ratio and performance maps for the NTF at constant Mach numbers from 0.1 to 1.2. The dashed lines on figure 3 are the estimated pressure ratios taken from reference 13 and updated to include the effects of the heat exchanger losses as installed, based on in-tunnel measurements of the pressure drop. The actual losses due to the heat exchanger were about twice as large as were allowed for in the pressure ratio estimates of reference 13.

The predicted benefits on pressure ratio of operation at high Reynolds numbers in nitrogen were apparently not fully obtained. This may have resulted in part because of losses associated with the injection of liquid nitrogen into the flow which were not included in the estimated pressure ratios. Another factor may be that the settings of the test section geometry were not necessarily optimum during the checkout phase when the pressure ratio measurements were made.

The rake shown in figure 4 was installed in the test section primarily to assess flow uniformity with respect to total pressure and temperature and will be discussed later in that regard. Since it provided a test section blockage ratio of about 0.5 percent, it was also useful in assessing model effects on tunnel pressure ratio. The measured variation in pressure ratio with the rake installed is shown in figure 5. Again, the dashed lines are estimates for the tunnel without a model and, therefore, are the same as shown on figure 3. The presence of the rake had only a small effect below a Mach number of 1.0. Above a Mach number of 1.0, a significant increase was noted. A model blockage of 0.5 percent, however, is excessively large for Mach numbers near 1.0 and would be prohibited due to excessive wall interference effects on the model data.

Figures 6, 7, and 8 show performance maps for the NTF at Mach numbers of 0.6, 0.8, and 1.0 respectively. These maps are essentially the same as the performance maps presented by Gloss and Nystrom[13], revised to reflect actual performance as obtained during the checkout operation of the NTF. The maps at constant Mach number show Reynolds number along the abscissa, as a function of total pressure along the ordinate, with lines of constant total temperature superimposed. The boundaries on these maps are formed on the bottom by the minimum operating pressure, on the left-hand side by the maximum operating temperature or by the maximum inlet guide vane performance, across the top by the maximum drive power available or by the maximum operating pressure, and on the right-hand side by the minimum operating temperature. Two minimum temperature lines are shown, one corresponding to saturation conditions at the free stream test section Mach number, and the other more conservative one for a local Mach number well above the free stream Mach number.

Some of the data points taken during the checkout phase are shown on the performance maps to indicate the range covered both in air and in nitrogen. The map boundaries on the upper left-hand side have been reduced somewhat from those shown in reference 13, once again reflecting the effect of higher losses in the tunnel circuit, and also lower inlet guide vane performance. The principal consequence of the reduction in the performance boundaries is a reduction in the range over which the Reynolds number can be varied at constant total pressure. Operation at constant total pressure corresponds to operation at constant dynamic pressure, and therefore, corresponds to relatively constant aeroelastic effects. Thus, there is a reduction in the Reynolds number range over which the aeroelastic effects can be held relatively constant at a given Mach number. The reduced range occurs only at the low Reynolds number end, and of course, the full Reynolds number range can still be covered but not all at constant pressure.

On the performance map for M=1.0 (figure 8), it may be seen that the highest data point obtained is at a Reynolds number of 117 X 10^6 which indicates that the design performance ($R_{\bar{c}}$ approximately 120 X 10^6 at M=1.0) for the NTF was substantially achieved. The maximum operating envelope showing Reynolds number as a function of Mach number is presented in figure 9, and gives a fairly complete picture of the range over which the NTF has been operated. The boundary lines and the lines of constant total and dynamic pressure correspond to operation at minimum cryogenic temperature.

The maximum Mach number achieved thus far in the checkout and calibration phase was 1.22, obtained in the cryogenic mode of operation in nitrogen at a pressure of 1.2 atm and at a temperature of 180K. In air, the maximum Mach number was 1.12 at a pressure of 1.4 atm and at a temperature of 320K. In both cases, the maximum design Mach number was 1.2.

Flow Stream Calibration

In preparing the NTF for operation, a comprehensive calibration plan was developed. This includes a steady-state calibration, where the basic tunnel flow characteristics are determined; a dynamic calibration where the flow turbulence is measured, an assessment of wall interference and flow blockage characteristics, and a comparison of NTF data with that obtained in other wind tunnels and in flight. A major portion of the steady-state calibration has been completed and will be discussed here.

While the emphasis for tunnel calibration was placed on the test section region, other areas of the circuit were instrumented in order to provide baseline information. As mentioned earlier, figure 1 shows the data measurement locations around the circuit. These generally consist of total temperature, total pressure, and static pressure measurements. The fan section measurements were shown in some detail in figure 2.

One of the early calibration activities was to obtain a uniform temperature distribution downstream of the cooling coil for air mode operation. This was accomplished using an array of thermocouples on the downstream side of the cooling coil positioned as shown in figure 10. A total of 63 thermocouples were used. The variation in temperature from the average of the thermocouples of 326.0K is shown for the top, middle, and bottom rows in figure 11. These data are for a test section Mach number of 0.997 at a total pressure of 1.22 bars. In general, the temperature at the downstream face of the coil is uniform within plus or minus 2 Kelvin. Temperature variations in the test section will be discussed later.

Two key reference measurements are made in the settling chamber of the tunnel as shown in figure 12. The reference total pressure is measured with a probe mounted in a strut downstream of the fourth screen. The reference temperature is measured by a platinum resistance thermometer located between the third and fourth screens.

Figure 13 illustrates the test section variable geometry and indicates relative locations of the test section static pressure orifices. The test section floor and ceiling pivot at the upstream end (station 0) and can be varied from one-half degree convergence to one degree divergence in order to accommodate variations in boundary layer over the operating envelope. The test section sidewalls are parallel to each other and will be solid (no slots) for the initial calibration. The floor and ceiling of the model support region (beginning of the diffuser) pivot at the downstream end and can be varied from 0° to 4.5° convergence. Reentry flaps in the slots are hinged to the front of the model support floor and ceiling. The reentry flaps move as a unit (although separate control for the top and bottom units is provided) over a range of 0° to 15° divergence relative to the model support floor or ceiling. The reentry flaps, in conjunction with the model support floor or ceiling, are positioned to accomplish an efficient reentry into the diffuser of the gas flows which have penetrated into the test section slots and plenum. Providing the proper test section geometry as a function of operating conditions is essential to obtaining a uniform test section Mach number distribution and reducing energy losses in the test section.

The test section Mach number distribution was determined utilizing the centerline pipe (illustrated in figure 14) in conjunction with the test section wall orifices. The upstream end of the centerline pipe extends past the test section throat (station zero) about 2.74 meters into the contraction cone. Forward support is provided by four cables (two horizontal and two vertical) which are swept forward from the pipe. The aft anchor point for the centerline pipe is the model support arc sector. A slight up-angle is provided at the aft mount point to minimize pipe sag in the primary region of the test section. This primary region extends from test section station 9 to station 17 where station 13 represents the center of rotation for the model support arc sector. The model center of rotation is maintained on the test section centerline. The centerline pipe is 7.6cm in diameter and has 320 static orifices 0.5mm in diameter. The prime row of orifices extends the length of the pipe at a nominal spacing of 7.6cm and with 2.5cm spacing near test section station 0 and for stations 9 to 17. In addition, at selected stations, orifices were placed on 90° centers around the pipe.

Using the centerline pipe, the test section Mach number distribution was determined as a function of total pressure, temperature and Mach number. The variable test section geometry was utilized during the calibration so as to optimize the Mach number distribution for various test conditions. Initially, geometry settings as a function of Mach number were established in the air mode of operation for low pressures and ambient temperatures. Thus, when operating in the cryogenic mode, only a minimum number of test points were required to determine the optimum test section settings for all operating conditions. The plenum static pressure was used as a reference value for calculation of test section Mach number during the calibration. Final selection of reference static pressure orifices will be made on the basis of the analysis of the calibration results.

An electronically scanned pressure (ESP) measurement system was used for obtaining pressure measurements. The ESP output was acquired, reduced, and displayed in a real time mode utilizing the onsite mini-computer data system. The ESP system provided a data snapshot of pressure measurements for a specific time, and hence, eliminates concern for changing pressure conditions during acquisition of a set of data.

The Mach number distribution at Mach numbers of 1.0 and below was expected to be uniform, therefore, the primary purpose of this part of the calibration was to obtain test section wall settings that would provide a zero longitudinal Mach number gradient through the test section. The results from this part of the calibration are still being analyzed. However, a typical variation of Mach number in the test region is shown in figure 15 and indicates a completely flat distribution over about a 2.4 meter test length.

In addition to calibrating the test section for Mach number distribution, the uniformity of test section flow with respect to total pressure and temperature, and flow anguiarity have been established. The survey rake illustrated in figure 4 was utilized to determine total pressure and temperature uniformity in the test section.

The rake had an array of twenty total pressures and ten total temperatures and was mounted in the NTF roll coupling (internal to the model support arc sector) to provide roll capability of $\pm 180^{\circ}$. The front of the rake was located at the arc sector center of rotation (station 13). The pressures were measured with the ESP system, and the thermocouples utilized an on-board reference junction to enhance measurement accuracy. The absolute level of the thermocouple measurements was anchored by a platinum resistance thermometer mounted in the settling chamber of the tunnel.

Figures 16 and 17 show typical variations of total pressure across the test section normalized by the reference total pressure. The two figures are for air operation at 324K and cryogenic at 122K, respectively. The reference line faired through the data is for a condition of zero gradient. It will be noted from an inspection of the data that a pressure gradient is not detectable in either the horizontal or vertical direction. Data taken at other radial cuts across the test section indicate the same result. This uniform profile is probably due to the streamline configuration and relatively high loss characteristics of the cooling coil located at the start of the settling chamber.

Figures 18 and 19 show typical variations in total temperature across the test section normalized by the reference total temperature. The data of figure 18 were taken in the air mode using the cooling coil. Again, the reference lines represent zero gradient. The distribution of data about this line is within plus or minus 1 Kelvin. The data of figure 19 were taken in the cryogenic mode using the liquid nitrogen injectors for cooling. These data generally fall within a band of plus or minus 0.5 Kelvin. It should be noted that the total temperature ratio is slightly higher than unity. This is due to an offset in the reference temperature junction which was not corrected during the test. This is not considered important for this discussion since the temperature uniformity across the test section, which was the primary item of interest, was unaffected.

A second blade exists for the survey rake which will accommodate flow angularity probes as well as hot wires or fluctuating pressure probes. The calibration plan includes a future survey of the test section to determine these effects. The measurements to be made are outlined in figure 20. In the interim, flow angularity has been investigated with the Pathfinder I model which is discussed later.

A description of planned calibration testing to assess wall interference, flow blockage characteristics, and the correlation of the NTF data with data from other wind tunnels and flight is presented in reference 14.

Pathfinder I

In December 1984, the Pathfinder I was installed in the NTF for checkout testing. This is a high aspect-ratio configuration with a solid supercritical wing. A sketch of the model with a few pertinent dimensions is shown in figure 21. The initial test program was to check out the model instrumentation and associated data acquisition and reduction programs. The on-board instrumentation includes a six-component strain gage force balance, six ESP modules, accelerometer type angle of attack unit, electrolytic bubble, and type-T thermocouples. On the tunnel was mounted a model laser angle of attack unit which utilized a retroreflector assembly mounted in the top of the Pathfinder, and a model deformation stereo video system which tracked targets on the left wing. Another accelerometer type angle of attack system was mounted at the downstream end of the model sting system for measuring sting deflection. A description of the instrumentation systems, along with requirements imposed by the cold testing environment and a discussion of the research and development activities to satisfy the environment, is given in reference 15.

Before installing the Pathfinder in the test section, the model was assembled and statically loaded in a model assembly bay at room temperature to primarily check the balance and software programs. Following, the Pathfinder was statically loaded at cryogenic temperatures using the cryogenic chamber described in reference 12 to check for temperature effects. Figures 22 and 23 shows the Pathfinder inside the chamber. In one view, the model is loaded for normal force and the other view is for side force. Figure 24 shows the relationship between the temperatures of the environment inside the chamber during cryogenic checkout and that of the model balance. During these tests, the balance output was checked as a function of temperature.

Figure 25 shows the Pathfinder I mounted in the NTF test section. The targets for the Model Video Deformation System can be seen on the left wing. Tunnel tests were performed in December 1984 in air at temperatures around 320K and in January 1985 in nitrogen at temperatures down to 116K. Data analysis is still ongoing, and hence, results are not available in time for inclusion in this report. However, this initial checkout of instrumentation systems was considered to be highly successful with all instrumentation systems operating. Further refinements will continue in order to improve performance on some systems at cryogenic temperature. The tunnel flow angularity was also investigated using the Pathfinder I model to obtain an integrated value of the flow angle by testing the model upright and inverted. The variation of normal force coefficient with model angle of attack for the model upright and inverted is shown in figure 26 for Mach numbers of 0.60 and 0.82. The near perfect agreement between the upright and inverted runs at both Mach numbers indicates that a correction for flow angle in the NTF at these test conditions will not be required.

Concluding Remarks

The construction of the National Transonic Facility was completed in September 1982, and shakedown operations started the following month, with the maximum Reynolds number being obtained in May 1983. In May 1984, the aerodynamic calibration of the tunnel commenced and was performed in parallel with checkout of the hardware systems, and in August of the same year the final operational readiness review was conducted and the facility declared operational for aerodynamic research and development testing.

The first phase of the flow uniformity calibration has been completed, and the first aerodynamic calibration model, Pathfinder I, was installed in December 1984 primarily for checkout of model instrumentation systems. The facility has been operated in both air and nitrogen modes covering a Mach number range of 0.2 to 1.22 at pressures up to 8.5 atm and at temperatures down to 100K. Some of the performance information obtained during shakedown and calibration is presented in this paper. Also, an outline of the overall calibration plans for the NTF is presented.

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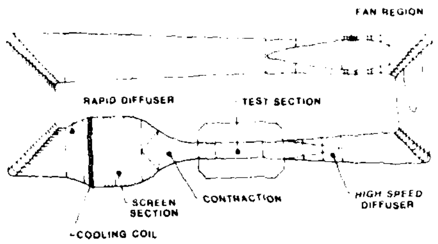

Figure 1.- Pressure and temperature data measurement locations around NTF circuit.

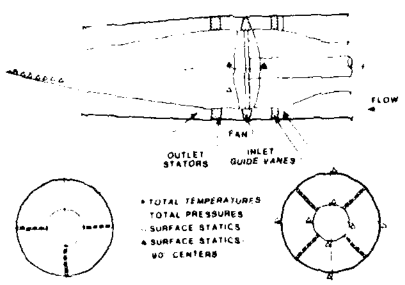

Figure 2.- Instrumentation on NTF fan nacelle.

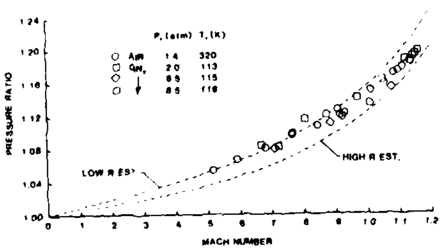

Figure 3.- Preliminary results of NTF pressure ratio measurements versus Mach number without a model installed.

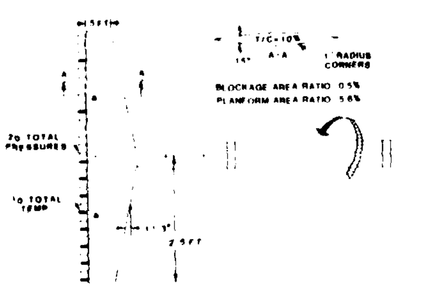

Figure 4.- NTF test section total pressure and temperature survey rake.

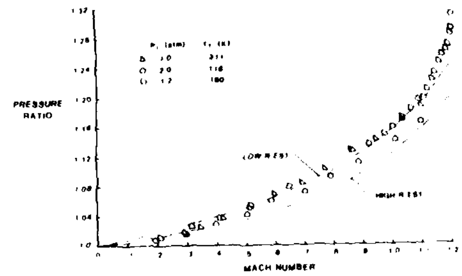

Figure 5.- Preliminary results of NTF pressure ratio measurement versus Mach number with survey rake installed.

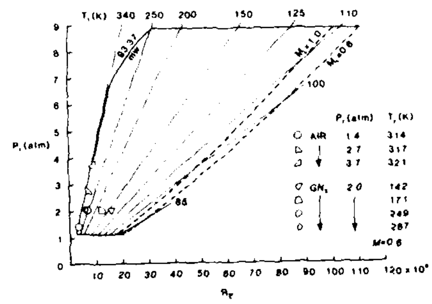

Figure 6.- Preliminary NTF performance map for M = 0.6.

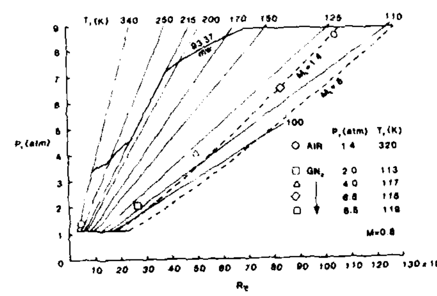

Figure 7.- Preliminary NTF performance map for M = 0.8.

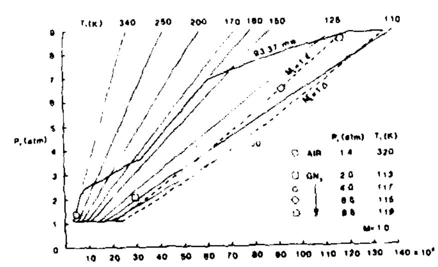

Figure 8.- Preliminary NTF performance map for M = 1.0.

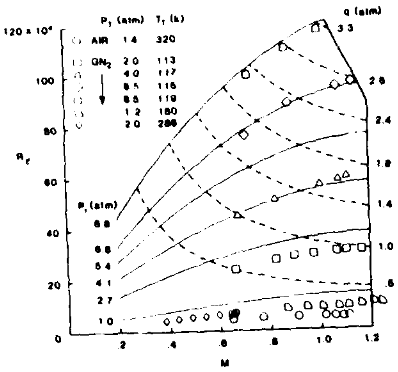

Figure 9.- Preliminary NTF operating Reynolds number envelope for minimum cryogenic temperature.

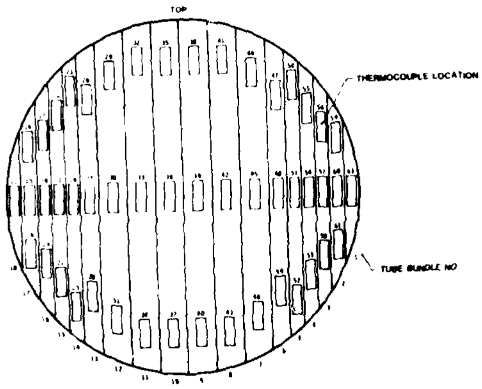

Figure 10.- NTF cooling coil showing location of the 63 thermocouples on the downstream face.

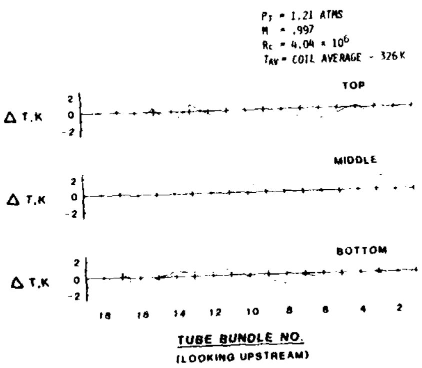

Figure 11.- Temperature variation for the top, middle and bottom rows of thermocouples on the NTF cooling coil face.

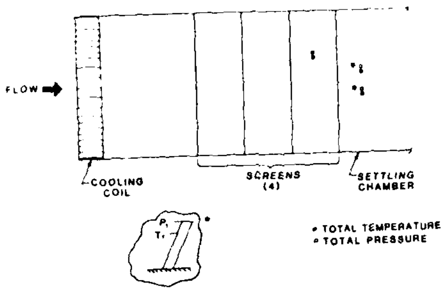

Figure 12.- NTF reference total pressure and total temperature measurement locations.

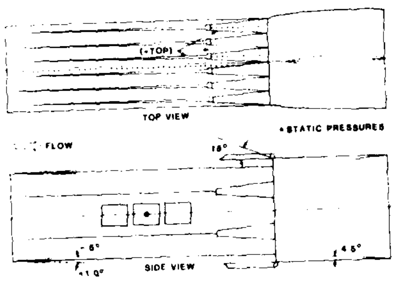

Figure 13.- NTF test section variable geometry and location of static pressure orifices.

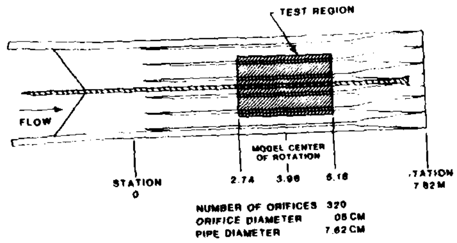

Figure 14.- NTF test section static pipe.

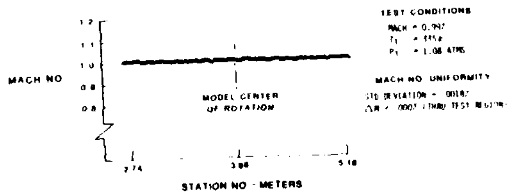

Figure 15.- Variation of Mach number in NTF test section.

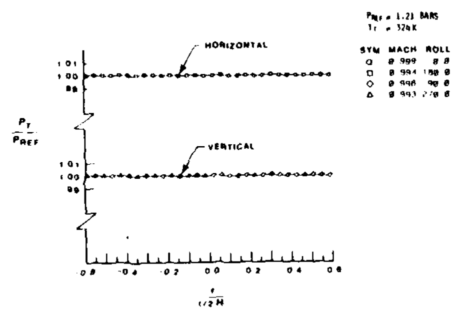

Figure 16.- Variation of total pressure across NTF test section, air operation.

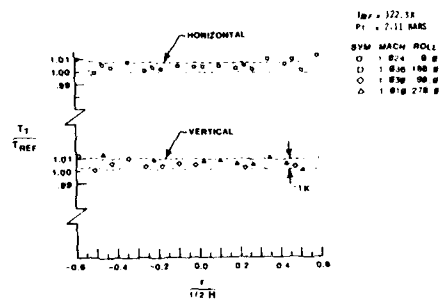

Figure 19.- Variation of total temperature across NTF test section, cryogenic operation.

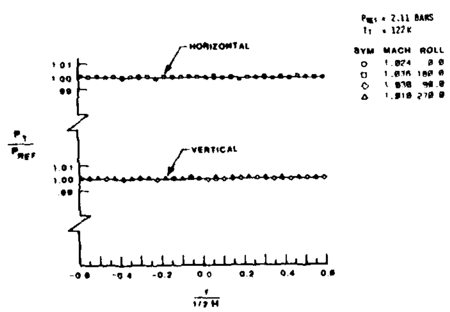

Figure 17.- Variation of total pressure across NTF test section, cryogenic operation.

- TEST SECTION $\tilde{u}$, $\tilde{\rho}$, $\tilde{T}_T$, $\tilde{P}$
  (THREE WIRE HOT WIRE PROBE AND PRESSURE PROBES)
- SETTLING CHAMBER, ACROSS SCREENS, ACROSS COOLER } $\tilde{u}$, $\tilde{v}$, $\tilde{w}$, $\tilde{T}_T$, $\tilde{P}$
  (FOUR WIRE HOT WIRE PROBE AND PRESSURE PROBE)
- DIFFUSER $\tilde{P}$
- SETTLING CHAMBER
  VARIATION IN THE MEAN VALUES OF ρ, u, T_T, P_T AS A FUNCTION OF TIME (THREE WIRE HOT WIRE PROBES AND PRESSURE TRANSDUCER)

Figure 20.- NTF dynamic flow quality calibration measurements.

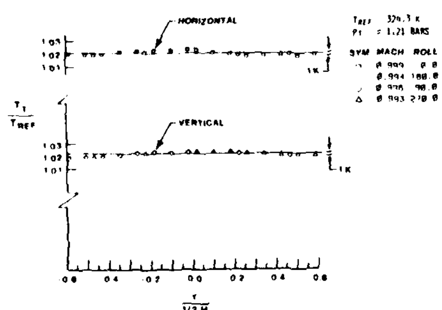

Figure 18.- Variation of total temperature across NTF test section, air operation.

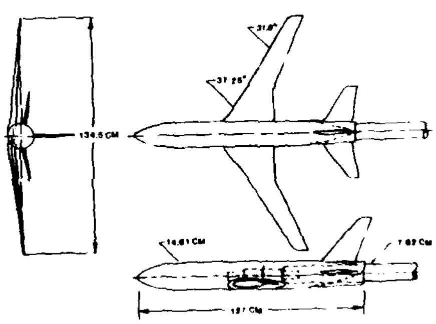

Figure 21.- Sketch of Pathfinder I.

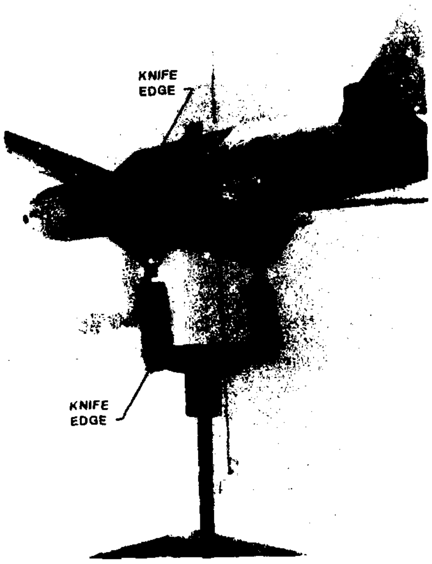

Figure 22.- NTF Pathfinder I in chamber with normal load for checkout at cryogenic temperature.

Figure 23.- NTF Pathfinder I in chamber with sideload for checkout at cryogenic temperature.

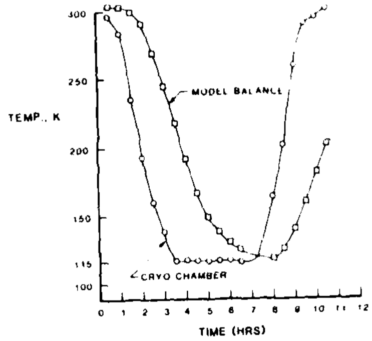

Figure 24.- Temperature history of cryo chamber and model balance during static checkout.

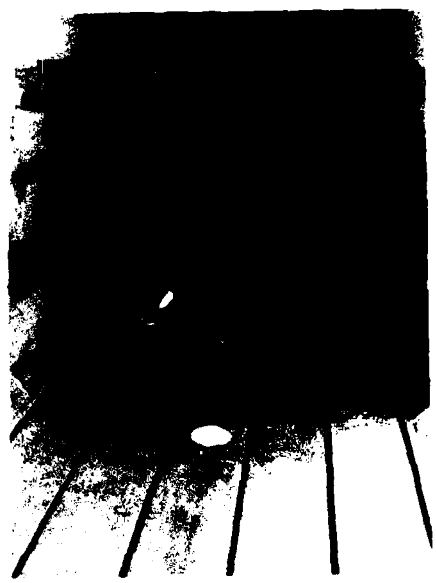

Figure 25.- Pathfinder I with solid wing mounted in the NTF test section.

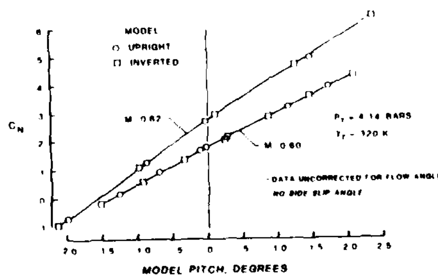

Figure 26.- Normal force coefficient as a function of model pitch for two Mach numbers as measured by the Pathfinder I model in the NTF test section.

OTHER CRYOGENIC WIND-TUNNEL PROJECTS

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SUMMARY

Following the development of the cryogenic wind tunnel at the NASA Langley Research Center in 1972, a large number of cryogenic wind-tunnel projects have been undertaken at various research establishments around the world. The purpose of this lecture is to describe some of the more significant cryogenic wind-tunnel projects not covered by other lecturers at this Special Course.

Described in this lecture are cryogenic wind-tunnel projects in **China** (Chinese Aeronautical Research and Development Center), **England** (College of Aeronautics at Cranfield, Royal Aircraft Establishment - Bedford, and University of Southampton), **Japan** (National Aerospace Laboratory, University of Tsukuba, and National Defense Academy), **Sweden** (Rollab), and the **United States** (Douglas Aircraft Co., University of Illinois at Urbana-Champaign, and NASA Langley).

1. INTRODUCTION

So far, in this series of lectures, we have heard about some of the cryogenic wind tunnel activities in the various member countries of AGARD. Mr. Bruce has described the U.S. National Transonic Facility (NTF) which is, by any account, the most significant transonic cryogenic tunnel project thus far completed. In a previous lecture, I described the Langley 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) which has been in continuous operation since 1973. The 0.3-m TCT has the distinction of being the first transonic cryogenic tunnel.

From Germany, we have heard from Dr. Viehweger of the DFVLR Kryo Kanal Koeln (KKK) which is the largest and most significant low-speed cryogenic tunnel project completed. Also from Germany, we have heard from Dr. Hefer of the DFVLR Cryogenic Ludwieg Tube Tunnel at Goettingen. We have heard Mr. Dor describe the various cryogenic wind tunnel activities in France. These activities include the work at the ONERA research center at Toulouse on T2 which, in addition to its ability to operate at cryogenic temperatures, has been successfully fitted with an adaptive-wall test section. Mr. Tizard has described the European Transonic Tunnel (ETW), perhaps the most ambitious cryogenic tunnel project next to the NTF.

The various lectures of this AGARD-FDP/VKI Special Course, taken together, indicate a very high level of cryogenic wind tunnel activity within the AGARD community. It should not be surprising, however, to learn that there are several other cryogenic tunnel projects, either completed or planned, in both AGARD and non-AGARD countries. It is my purpose in this lecture to describe briefly some of these cryogenic tunnel projects, giving as much technical detail about each as I have been able to gather, either by personal observation or through the generous cooperation of persons directly involved with each project.

In order to explain the absence of some cryogenic wind-tunnel projects from this lecture, it should be noted that no attempt has been made to describe all of the projects not otherwise covered in this series of lectures. Rather, the various projects described in the following pages have been selected to illustrate the wide variety of cryogenic wind-tunnel projects which have arisen since the first cryogenic wind tunnel was built at NASA Langley in 1972.

Much of the information with respect to the various tunnel projects is presented in tables. An entry of "?" indicates that information is not available at the time the written version of this lecture was being typed. For some of the projects still in the study or planning stages, final design decisions have not been made. For these cases, the table entry is "to be determined." Unless otherwise specified, the value of Reynolds number is given per metre. Considerable effort has been made to verify the accuracy of the "factual" information contained in this lecture. However, the reader is advised to contact directly the people involved with each of the projects for more detailed information, particularly with respect to the status of on going projects.

2. CHINA

Since 1975, researchers at the Chinese Aerodynamic Research and Development Center (CARDC), Mianyang, Sichuan, China, have studied various schemes for high Reynolds number transonic wind tunnels including the cryogenic nitrogen wind tunnel. They have concluded from their studies that the continuous flow cryogenic nitrogen tunnel is particularly attractive for meeting their high Reynolds number transonic testing requirements. However, due to the relatively high initial cost of a continuous flow cryogenic tunnel, the researchers at CARDC have studied alternate intermittent cryogenic wind-tunnel schemes as a way of achieving the required high Reynolds numbers at less cost. The results of their studies are reported in Reference 1.

The intermittent cryogenic tunnel scheme being proposed by CARDC would use precooled high pressure air which is further cooled by throttling before passing through the wind tunnel test section into a storage tank. As noted in Reference 1, the capital cost of the proposed cryogenic tunnel is greatly reduced by taking advantage of an existing high pressure air storage system.

The major characteristics of the proposed CARDC 2.4 x 2.4 m high Reynolds number cryogenic transonic wind tunnel are listed in Table 1.

To achieve the specified test Reynolds number, both stagnation pressure and temperature will be varied with Mach number. For example, at a Mach number of 0.8, the stagnation pressure would be 506 kPa and the stagnation temperature would be 154 K. It was indicated in Reference 1 that stagnation pressures up to 1013 kPa could be used with stagnation temperatures varying from ambient to a lower limit set by the condensation boundary for air.

TABLE 1. - Characteristics of Proposed Cryogenic Transonic Tunnel at CARDC (China)

Type......................	intermittent
Material of construction...	?
Insulation.................	?
Cooling....................	throttling
Test gas...................	air
Test section size (h,w,l)..	2.4 x 2.4 x ? m
Mach range.................	0.5 - 1.6
Contraction ratio..........	?
Stagnation pressure........	up to 1013 kPa
Stagnation temperature.....	sat. to ambient
Running time...............	?
Max. Reynolds number/m.....	167 million

The CARDC intermittent cryogenic wind tunnel will consist of an existing high pressure air supply system, the various components of the wind tunnel, and a system for collecting the cold air which has passed through the test section. A schematic diagram of the proposed tunnel is shown in Figure 1.

There are five axial-flow compressors in the existing high pressure air supply system, each capable of compressing 130 m^3 per minute to 22.3 MPa (220 atm). The high pressure storage tanks are made of 09Mn2VR low temperature steel and have a total volume of about 1290 m^3. The initial filling time for the storage tanks is about 5 hours. During normal operation, where the pressure in the storage tanks is not reduced below 15.2 MPa (150 atm), filling time is about 2 hours. The precooling system not only cools the compressed air but also reduces the water content to less than 0.2 gram per kg of air. Two heat exchangers are alternately used, one operating while the other is defrosting.

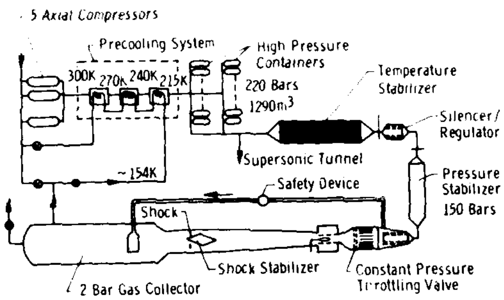

Fig. 1 CARDC 2.4 x 2.4 m high Reynolds number transonic wind tunnel. [Figure from Ref. 1]

There will be constant temperature equipment to compensate for the temperature reduction in the air expanding adiabatically in the high pressure container. Altogether, 636 x 10^3 kg of FL5 aluminum alloy will be used in the constant temperature equipment. As explained in Reference 1, the relatively large pressure regulating valve and the constant pressure throttling valve will be very important elements in the tunnel control system.

There will be a shock wave stabilizer in the last part of the wind tunnel diffuser. It will be used to control the position of the shock wave in order to hold the test section Mach number constant. During a test, the air pressure in the collecting container will increase continuously. The shock wave of the wave stabilizer will continuously move forward, but the wave stabilizer will make the shock wave stabilize at the downstream end of the throat to keep the test Mach number constant.

The air container will be used to collect the low temperature air after it has passed through the test section. A portion of the air will be used to cool the pre-cooling system. The remainder of the air will be recompressed and stored in the storage tanks. A typical volume envisioned for the air collecting container will be about 2.7-3.6 x 10^4 m^3. Under conditions where low temperature air must be exhausted directly to the atmosphere, provision will be made to increase the temperature of the air so as to avoid problems with fogging.

3. ENGLAND

3.1 College of Aeronautics, Cranfield

Schultz and his co-workers at Oxford University proposed and built an isentropic light piston tunnel (ILPT) to measure heat transfer rate on gas turbine blades in a short duration, hot, low-Reynolds-number flow.[2] The ILPT is shown schematically in Figure 2.

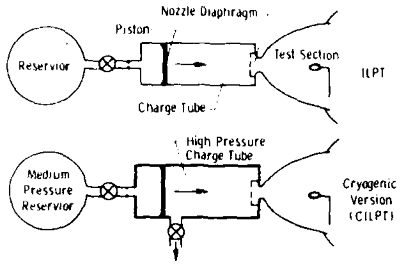

Fig. 2 Cryogenic ILPT compared with standard version. [Ref. 3]

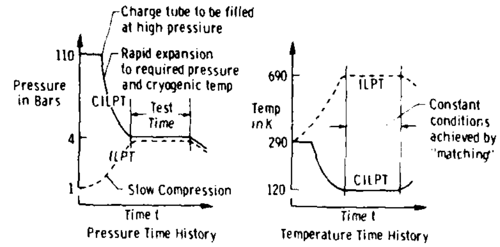

Fig. 3 Pressure and temperature time histories for cryogenic and standard ILPT. [Ref. 4]

In this tunnel concept, a light piston is driven by compressed air into a charge tube, *compressing and heating the gas in the tube almost isentropically.* The piston acts as a barrier between the compressed air expanding into the charge tube and the gas in the charge tube which is being compressed. When the desired pressure and temperature are reached by the gas in the charge tube, a fast-acting valve (or diaphragm) at the end of the charge tube is opened to allow the hot test gas to pass through the test section. The tunnel is designed so that the volumetric flow of compressed air from the reservoir into the charge tube *exactly matches the flow* of gas from the charge tube through the test section. By matching the flows in this way, constant test conditions are maintained.

At the College of Aeronautics, Cranfield Institute of Technology, Bedford, Stollery and Murthy suggested that the Oxford type of light piston tunnel could be operated in *reverse in order to achieve* intermittent, **low-temperature**, high-Reynolds-number flows.[5] The scheme for the cryogenic isentropic light piston tunnel (CILPT) is shown in Figure 2 in its simplest form in which high pressure gas in the charge tube is vented to the atmosphere. When the vent valve is opened, the pressure and temperature in the charge tube expand isentropically to the values required for the test, whereupon the vent valve is closed. The valve separating the test section from the charge tube is opened, and following a predetermined delay of a few milliseconds, the piston is set in motion by opening the valve between the charge tube and the medium pressure reservoir, thereby pushing the cold gas in the charge tube out through the test section. Again, by matching the incoming and outgoing volumetric flows, constant test conditions are maintained. The idealized pressure and temperature time history for both the ILPT and the cryogenic version of the ILPT are shown in Figure 3.

TABLE 2.- Characteristics of Pilot *Cryogenic Isentropic Light Piston Tunnel* at Cranfield (England)

Type......................	isentropic expansion, light piston
Material of construction...	stainless steel
Insulation................	none
Cooling...................	isentropic expansion
Test gas..................	nitrogen
Charge tube pressure.......	up to 3549 kPa
Test section size (h,w,l)..	2.86 x 2.86 x 15 cm
Mach range................	transonic
Contraction ratio..........	6:1
Stagnation pressure........	100 kPa
Stagnation temperature.....	down to 110 K
Running time...............	0.3 s
Max. Reynolds number/m.....	42 million

A pilot intermittent cryogenic wind tunnel based on this light piston concept has been constructed and tested at the College of Aeronautics. Using nitrogen as the test gas, both the low stagnation temperature and the required matching of volumetric flows have been achieved. A very thorough analysis of the CILPT as well as the design details of the pilot CILPT and experimental results obtained from the tunnel are given in Reference 6. The major characteristics of the pilot CILPT at Cranfield are listed in Table 2. The general arrangement of the pilot CILPT is shown in Figure 4.

Preliminary studies have been made of much larger versions of the CILPT by Stollery and his co-workers.[5] For example, when the original specifications for the cryogenic version of the proposed European Transonic Windtunnel are assumed, i.e., p_t = 440 kPa (4.4 bars), T_t = 120 K, 1.95 x 1.65 m test section and $R_{\bar{c}}$ = 40 million at M = 0.9, the total test mass required for 10 seconds running time is 53,000 kg. The corresponding charge tube volume is 4060 m^3 which would require, for example, a 4 m diameter cylinder over 300 m long.

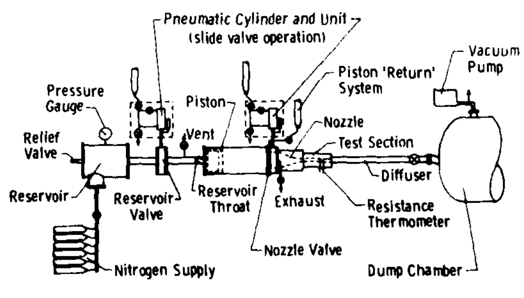

Fig. 4 General arrangement of Pilot CILPT at Cranfield. [Ref. 6]

In order to achieve the required temperature during the expansion process, the ideal pressure ratio through which the gas must be expanded is 25:1. Thus, part of the charge tube must be stressed to accommodate pressures of 11 MPa (110 bars).

In fact, departure from the ideal, caused by heat transfer from the walls of the charge tube to the gas, requires that the gas be expanded through a considerably larger ratio. Typically, to achieve a stagnation temperature of 120 K from an initial temperature of 300 K, an expansion ratio of about 35:1 will be required.[3]

If the CILPT concept were used to achieve the maximum design Reynolds number of 120 million of the 2.5 x 2.5 m U.S. National Transonic Facility (NTF) at the design maximum stagnation pressure of 880 kPa (8.8 bars), the test mass would be 194,000 kg stored in a 7400 m^3 charge tube at 22 MPa (220 bars).

As noted in Reference 5, CILPT versions of the ETW or the NTF would be very large facilities but would also have the virtue of being extremely simple. It is also noted that concerns remain over the quality of the flow in such facilities as well as possible variations in the stagnation temperature during the run due to heat transfer from the charge tube to the gas.

A more modest application of the CILPT was also studied. An example given in Reference 5 assumed an arbitrary structural limit of 600 kPa (6 bars) and a 0.6 x 0.6 m test section designed for M = 0.9. The charge tube volume required for a 1 second run would be a modest 47 m^3, e.g. a 2 m diameter cylinder 15 m long. Such a facility could achieve a Reynolds number of 19 million compared to 5.2 million for a straight blowdown tunnel operating at p_t = 600 kPa (6 bars) and T_t = 300 K.

3.2 Royal Aircraft Establishment - Bedford

A closed circuit Cryogenic Test Duct has been constructed at the Royal Aircraft Establishment (RAE), Bedford as part of the United Kingdom support for the European Transonic Windtunnel (ETW) program.[7] The Test Duct is used as an inexpensive and convenient way of providing a cryogenic environment for testing wind tunnel balances and model components under realistic conditions of gas flow. The maximum gas velocity through the 0.3 m square test section is 25 m/s, falling with temperature. By controlling the rate of injection of LN_2 in the circuit, the gas temperature can rapidly be reduced and controlled at any level between ambient and 90 K.

The Test Duct was fitted with external insulation for the early experiments. The external insulation consists of a plywood shroud containing vermiculite in a 10 cm gap between the plywood and the aluminum Duct. A dry nitrogen purge is provided in the insulation space for dryness and to reduce the chance of oxygen enrichment. Recently, in a successful effort to increase the rate at which temperature can be changed, about 75 percent of the inner surface of the Duct has been lined with a 3 mm thick layer of either cork or FEP insulation.

TABLE 3.- Characteristics of Cryogenic Test Duct at RAE-Bedford (England)

Type	**closed circuit, centrifugal fan**
Material of construction	**aluminum**
Insulation	**external and internal**
Cooling	**liquid nitrogen**
Test gas	**nitrogen**
Test section size (h,w,l)	**0.3 x 0.3 x 1.5 m**
Speed range	**up to 25 m/s**
Contraction ratio	**1:1**
Stagnation pressure	**atmospheric**
Stagnation temperature	**90 K - ambient**
Running time	**typically 1 hour**
Max. Reynolds number/m	**11.4 million**
Drive motor	**9 kW**
Fan speed	**up to 2500 rpm**
LN_2 tank volume	**1.28 m^3**

The major characteristics of the Cryogenic Test Duct at RAE - Bedford are given in Table 3. The general arrangement of the Test Duct is shown in the photograph of Figure 5, taken before the Duct was insulated.

A simple calibration device is provided for loading small wind tunnel balances mounted in the test section and some observations have been made of the behavior of a 3-component balance under transient temperature conditions. In addition, the test section of the Duct has transparent sides which allow direct visual observation during tests. Details of the design and operational characteristics of the RAE Cryogenic Test Facility and some of the test results obtained on the NLR 771 strain gage balance are given in Reference 7.

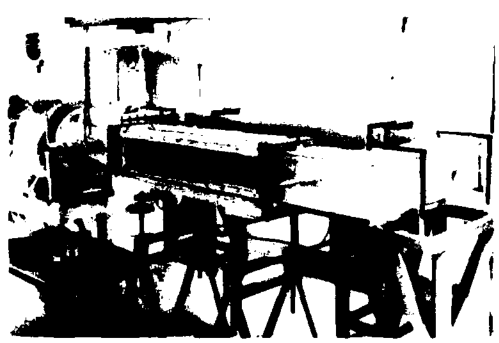

Fig. 5 Photograph of RAE - Bedford Cryogenic Test Duct. [Ref. 7]

3.3 University of Southampton

Dr. M. J. Goodyer of the University of Southampton must be given credit for starting this era of cryogenic tunnels. While working on magnetic suspension and balance systems (MSBSs) at the NASA Langley Research Center in 1971, Dr. Goodyer suggested the use of either air or nitrogen at cryogenic test temperatures as a way of increasing the test Reynolds number in the small wind tunnels equipped with MSBSs. Goodyer's proposal seemed reasonable, not only for tunnels of modest size fitted with MSBSs, but also for large tunnels that would be capable of testing models at or near full-scale values of Reynolds number. Because of the urgent need for a reasonable size transonic tunnel capable of testing at or near full-scale Reynolds numbers, the work at Langley on MSBSs was temporarily set aside as a small team of researchers set out to solve any practical problems that might be found in trying to make the cryogenic wind tunnel concept work.

That our efforts were successful is demonstrated by the fact that the U.S. National Transonic Facility (NTF) is now in operation. In recognition of his contribution to the NTF, Dr. Goodyer was awarded the NASA Exceptional Scientific Achievement Medal in 1984 "for scientific contributions in proposing and verifying the cryogenic wind tunnel concept which led to the development of the National Transonic Facility."

Since returning to Southampton in 1972, Dr. Goodyer has continued to work with researchers at Langley through various grants and contracts in the areas of cryogenic tunnels, MSBS, and adaptive wall test sections.

His work at Southampton has been extremely productive, especially in his efforts to develop, demonstrate and perfect various improvements in testing techniques. As an integral part of this effort, Dr. Goodyer and his co-workers in the Department of Aeronautics and Astronautics have designed and built a very successful low-speed cryogenic tunnel.

3.3.1 Low-speed cryogenic tunnel

This low-speed cryogenic tunnel has been described, in some detail, by Goodyer in the opening lecture[8] of this Special Course and, except for the basic specifications and some interesting features, will not be repeated here.

Since it was first operated at cryogenic temperatures on March 4, 1977,[9] it has accumulated about 35 hours of operation at temperatures less than 150 K. Materials of construction include aluminum, glass fiber reinforced polyester, polycarbonate, resin impregnated glass laminate, stainless steel, brass, copper, and glass. This tunnel has evolved into a very sophisticated facility with several improvements having been made since being commissioned in 1977.[10] For example, it has been equipped with an automatic control system capable of holding either Mach number or Reynolds number constant.[11]

Finally realizing the goal which prompted the original cryogenic wind tunnel research at Langley in 1971-72, the Southampton low-speed cryogenic tunnel was modified in 1978 and used[12] in conjunction with the Southampton 6-component magnetic suspension and balance system.

The basic specifications for the Southampton low-speed cryogenic tunnel are given in Table 4.

As with many low-speed cryogenic tunnels, electric heaters were added to the circuit to speed up the warming of the tunnel following cryogenic operation. In addition, they provide an easy way to achieve close control of total temperature when a slight excess of liquid nitrogen is injected over that required to balance the heat added to the stream by the fan. In the Southampton tunnel, they provide a unique ability to operate at temperatures up to 380 K (+ 105°C, + 221°F) by using the three 1 kW electric heaters to supplement the heat added to the stream by the drive fan. The ability to operate at elevated temperatures provides a greatly increased range of test Reynolds numbers.

TABLE 4.- Characteristics of Cryogenic Low-Speed Tunnel at Southampton (England)

Type	closed circuit, fan
Material of construction	mostly aluminum
Insulation	external
Cooling	liquid nitrogen
Test gas	nitrogen; air (when running hot)
Test section size (h,w,l)	
Regular	0.11 x 0.11 x 0.25 m
MSBS	0.14 x 0.11 x 0.41 m
Speed range	14 - 72 m/s
Mach range	0.04 - 0.40
Contraction ratio	5.4:1
Stagnation pressure	atmospheric
Stagnation temperature	79 - 380 K
Running time	typically 1 hour
Max. Reynolds number/m	50 million
Drive motor	4 kW
Fan speed	up to 7200 rpm
LN_2 tank volume	0.17 m^3

The Southampton low-speed tunnel has been used for a variety of purposes, some taking advantage of the fact that the "regular" test section is fitted with windows in the top and side. An early application was the successful development of a surface flow visualization technique using a pigment suspended in liquid propane (C_3H_8).[13] Also, a variety of tuft materials, including wool and cotton, were shown to be usable to the lowest temperatures obtainable, i.e., 79 K.

Extensive studies, using thermocouple probes with response compensation, were made in an unsuccessful attempt to discover the illusive "temperature spottiness" (thermal turbulence) which some researchers had feared would make testing in cryogenic tunnels impossible.

3.3.2 Cryogenic isentropic free piston expander

The cryogenic isentropic light piston tunnel proposed by Stollery and Murthy[5] has also been the subject of study at Southampton by Hutt and East.[14] In addition to their desire to test the feasibility of the concept, another purpose of the work at Southampton was to investigate methods of measuring temperature during the relatively short expansion and expulsion phases of operation. During the study, two charge tubes were built and tested. Both of the charge tubes were used in conjunction with an "instrumentation assembly" which allowed various temperature measuring devices to be tested.

The first charge tube tested had a length to diameter, (ℓ/d), ratio of 23 and was not able to achieve cryogenic conditions, that is, temperatures of 172 K or less, with pressure expansion ratios up to 25:1. The lowest temperature achieved with the first charge tube was 190 K. The second charge tube had an ℓ/d of 0.22 and could successfully achieve cryogenic conditions (i.e., 172 K or less) with expansion ratios as low as about 10:1. At an expansion ratio of 25:1, temperatures of 145 K were achieved.

The major characteristics of the Southampton free piston expander using the ℓ/d = 0.22 charge tube are given in Table 5. The instrumentation assembly was vented to the atmosphere through a 3 mm throat diameter sonic nozzle and there was no test section, in the usual sense, ever used with either of the charge tubes. Therefore, certain items in Table 5 are left blank.

The detailed results of the studies of the free piston expander by Hutt and East are reported in Reference 14. A major accomplishment of the work at Southampton is that it provided the first demonstration of the CILPT concept of Stollery and Murthy when cryogenic conditions were first achieved on March 1, 1979. The work at Southampton also convincingly demonstrated the superiority of charge tubes having low ratios of ℓ/d. Based on their work, Hutt and East have suggested that improved performance of an isentropic expansion device could be achieved if the charge tube were replaced with a spherical pressure vessel and the light piston replaced with a flexible diaphragm.

TABLE 5.- Characteristics of Cryogenic Free-Piston Expander at Southampton (England)

Type	**isentropic expansion, light piston**
Material of construction	**mild steel**
Insulation	**none**
Cooling	**isentropic expansion**
Test gas	**nitrogen**
Charge tube pressure	**5000 kPa (50 bars)**
Test section size (h,w,l)	
Mach range	
Contraction ratio	
Stagnation pressure	**200 kPa**
Stagnation temperature	**145 K**
Running time	**1.6 s**
Max. Reynolds number	

4. JAPAN

It is somewhat of an understatement to say that there is considerable cryogenic wind tunnel activity in Japan. In May of 1982, I visited Japan and was able to see firsthand several of their cryogenic tunnels and meet the people involved with their development. I also was able to discuss with representatives of Japan Steel their considerable involvement in the U.S. National Transonic Facility by supplying, as a subcontractor, the drive shaft, fan disk, and sting support arc sector. It was obvious to me in 1982 that Japan had more than a passing interest in the development and exploitation of cryogenic wind tunnels. I have been able to maintain close technical contact with my friends in Japan who have very kindly provided me with up-to-date information on the various cryogenic tunnel projects described in this section.

4.1 National Aerospace Laboratory (NAL)

Even though Japan has many excellent wind tunnels, particularly at the National Aerospace Laboratory (NAL) in Tokyo, aeronautical researchers in Japan have long recognized the need for tunnels capable of testing closer to flight Reynolds numbers, particularly at transonic speeds. As a first step toward meeting this need, a high Reynolds number transonic tunnel based on high pressure operation at ambient temperature was completed at NAL in 1979. This wind tunnel, which has a 0.3 x 1.0 m two-dimensional test section, can test airfoils at Reynolds numbers up to 40 million.[15,16] However, in order to meet the high Reynolds number testing requirements for three-dimensional testing at transonic speeds, it is generally recognized that a relatively large wind tunnel capable of cryogenic operation is required.[17] There is, therefore, considerable interest and activity in cryogenic wind tunnels at NAL.

A small pilot transonic cryogenic tunnel was built in 1982 and is being used by researchers at NAL to provide operational experience and support for design studies of a larger transonic cryogenic tunnel for Japan.

4.1.1 0.1 x 0.1 m Pilot Transonic Cryogenic Tunnel

The 0.1 x 0.1 m Pilot Transonic Cryogenic Tunnel at NAL was designed and built by Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI), a company which has been the general contractor for all of the cryogenic wind tunnels built in Japan.

The major characteristics of the NAL 0.1 x 0.1 m Pilot Transonic Cryogenic Tunnel are given in Table 6. A general view of this tunnel is shown in Figure 6.

The pressure shell is welded from 5 mm thick plates of A5052 aluminum alloy with flanged and bolted joints. The shell is fixed at the fan section and allowed to slide on 1 cm thick teflon pads at other support points to accommodate thermal expansion and contraction. A photograph of the tunnel taken before it was insulated is shown in Figure 7.

TABLE 6.- Characteristics of Pilot Transonic Cryogenic Tunnel at NAL (Japan)

Type	closed circuit, fan
Material of construction	A5052 Al-alloy
Insulation	external, purged
Cooling	liquid nitrogen
Test gas	nitrogen
Test section size (h,w,l)	0.1 x 0.1 x 0.3 m
Mach range	up to 1.02
Contraction ratio	18.1:1
Stagnation pressure	200 kPa
Stagnation temperature	90 K - ambient
Running time	more than 2 hours
Max. Reynolds number/m	130 million
Drive motor	55 kW
Fan speed	600 - 5700 rpm
LN_2 tank volume	2.17 m^3

The 10 cm thick thermal insulation for the tunnel consists of four layers of glass wool applied to the outside of the tunnel. The glass wool insulation is covered with a sheet metal vapor barrier and is purged with dry nitrogen. This insulation has proven to be satisfactory from the thermal point of view. However, the glass wool has proven to be highly irritating to the skin of the tunnel technicians and is being replaced with a less irritating insulation.

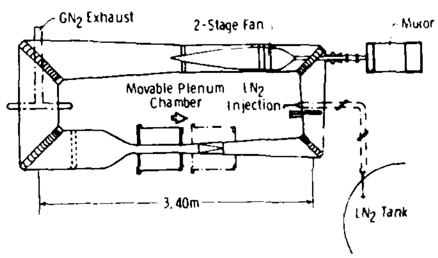

Fig. 6 Sketch of NAL 0.1 x 0.1 m tunnel.

Liquid nitrogen is supplied to the tunnel from a 2.17 m^3 storage tank placed outside the building housing the tunnel but still relatively near the tunnel. Rather than use a pump, the liquid nitrogen is simply forced into the tunnel by increasing the pressure in the storage tank using a pressurization coil.

Liquid nitrogen at rates up to 20 litres per minute is injected through four spray nozzles installed between the first and second corners. The flow rate is controlled by a manually operated valve and measured using a turbine type flowmeter. Two 6-cm diameter glass windows are fitted at the injection station to allow observation of the injection process.

Gaseous nitrogen is exhausted from the tunnel between the third and fourth corners. In a design similar to the 0.3-m TCT at Langley, three exhaust pipes come from the tunnel at 120° intervals in order to minimize disturbances. A remotely controlled pneumatic valve is used, at times in combination with a manually controlled valve, to control the exhaust flow rate over a wide range. The exhaust is dumped directly to the atmosphere through a single un-insulated 18-8 stainless steel pipe.

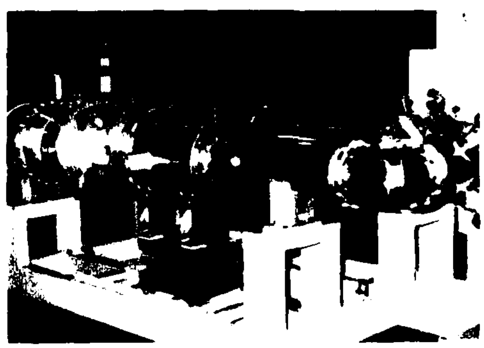

Fig. 7 Photograph of un-insulated NAL 0.1 x 0.1 m tunnel.

A 55 kW squirrel cage induction motor with variable frequency speed control drives a two-stage fixed-geometry fan with 12 blades. The motor, which is external to the tunnel, is capable of operating at speeds from 600 to 6000 rpm. However, operation is presently limited to speeds below 5700 rpm due to the excitation of resonance in the drive shaft.

The fan bearing inside the tunnel was initially fitted with a 0.5 kW heater. However, the position of the heater was not appropriate and the power was inadequate, a combination of circumstances which resulted in some serious problems due to dimensional changes and freezing of the lubricating oil. These problems have been solved by fitting the fan bearing with a 1 kW electric heater.

Two screens of 30-mesh are installed ahead of the contraction section which has a very respectable 18.1:1 ratio. The test section is enclosed in a 0.52 m internal diameter plenum chamber. The top and bottom walls of the test section are perforated with an open-area ratio of 20 percent. Adjustable reentry flaps are used to control the amount of diffuser suction. Access to the test section is provided by moving the plenum chamber shell telescopically downstream after the thermal insulation in the test section area has been removed.

Stagnation and plenum pressures are measured by strain-gage type pressure transducers. Total temperature is measured by a resistance thermometer and the shell temperature at various stations is measured using copper-constantan thermocouples. These quantities, along with motor speed, liquid nitrogen flow rate, and dew point temperature of the gas in the tunnel, are recorded using a data logger and a dedicated microcomputer.

A wide variety of operational tests have been made in the 0.1 x 0.1 m pilot tunnel. The typical purging, cool down, running, and warmup sequences have been performed using the presently installed manual control systems for LN_2 injection, GN_2 exhaust, and fan speed. Because of the manual control, changing from one set of test conditions to another normally takes from 5 to 10 minutes.

The operating envelope of the tunnel has been explored with particular emphasis on temperatures between 95 and 125 K. Tunnel characteristics such as power factor and transient responses to changes in fan speed and LN_2 flow rate have been determined. In all respects, the tunnel performs satisfactorily and as predicted.

Future plans for the 0.1 x 0.1 m tunnel include automation of the tunnel controls for LN_2 injection, making a detailed study of the characteristics of the tunnel over the entire operating envelope, and performing aerodynamic tests on some simple shapes.

4.1.2 0.6 x 0.6 m Transonic Cryogenic Tunnel

Based on their highly successful experience to date with the 0.1 x 0.1 m Pilot Transonic Cryogenic Tunnel, the researchers at NAL are studying a fan-driven transonic cryogenic tunnel having the characteristics given in Table 7. The minimum test section size being considered for this tunnel would be 0.6 x 0.6 m with a larger test section likely in order to permit greater detail in the models. However, even at the minimum size, the relatively high operating pressure gives a Reynolds number of 20 million based on 0.06 m.

TABLE 7.- Characteristics of Transonic Cryogenic Tunnel under study at NAL (Japan)

Type......................	closed circuit, fan
Material of construction...	(to be determined)
Insulation................	(to be determined)
Cooling...................	liquid nitrogen
Test gas..................	nitrogen
Test section size (h,w,l)..	0.6 x 0.6 x 2 m (minimum)
Mach range................	0.2 - 1.2
Contraction ratio.........	19.6:1
Stagnation pressure........	500 kPa (possibly 800 kPa)
Stagnation temperature.....	100 K - ambient
Running time..............	1 - 2 hours
Max. Reynolds number/m.....	333 million
Drive motor...............	5 MW
Fan speed.................	up to 1200 rpm
LN_2 tank volume...........	1000 m^3

4.2 University of Tsukuba

The Institute of Engineering Mechanics at the University of Tsukuba, Sakura, Ibaraki, Japan, has two low-speed cryogenic wind tunnels. One has a 0.1 x 0.1 m test section and the other a 0.5 x 0.5 m test section.

4.2.1 0.1 x 0.1 m Low-Speed Cryogenic Tunnel

The 0.1 x 0.1 m low-speed cryogenic tunnel was first operated at cryogenic conditions in 1980. It has been used mainly for research by graduate students, for the calibration of sensors, and to provide operational experience with cryogenic tunnels. In addition, it furnished valuable design information needed for the larger low-speed tunnel.

Because of the relatively small size of this tunnel, it is unlikely to be used in the future for much serious aerodynamic research, especially since a much larger and more sophisticated low-speed tunnel, described in the following section, is now available for the researchers at Tsukuba.

A photograph of the 0.1 x 0.1 m low-speed tunnel at Tsukuba is shown in Figure 8. In this view, the flow is counterclockwise. LN_2 is injected into the high speed diffuser at the upper left and the GN_2 exhaust taken from the crossleg at the right.

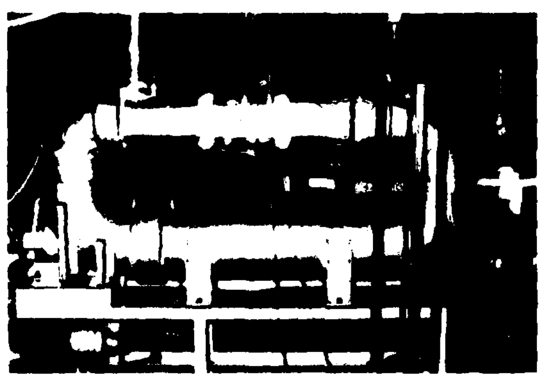

Fig. 8 Photograph of 0.1 x 0.1 m low-speed tunnel at Tsukuba.

The basic specifications for the 0.1 x 0.1 m low-speed cryogenic tunnel at Tsukuba are given in Table 8.

TABLE 8.- Characteristics of 0.1 x 0.1 m Low-Speed Cryogenic Tunnel at Tsukuba (Japan)

Type....................	closed circuit, fan
Material of construction...	stainless steel
Insulation.................	external
Cooling....................	liquid nitrogen
Test gas...................	nitrogen
Test section size (h,w,l)..	0.1 x 0.1 x 0.3 m
Speed range................	up to 30 m/s
Contraction ratio..........	3.41:1
Stagnation pressure........	up to 203 kPa
Stagnation temperature.....	100 K - ambient
Running time...............	up to 2 hours
Max. Reynolds number/m.....	30 million
Drive motor................	2.2 kW
Fan speed..................	1500 - 4300 rpm
LN_2 tank volume............	175 litre

4.2.2 0.5 x 0.5 m Cryogenic Tunnel

The general contractor for the 0.5 x 0.5 m low-speed cryogenic tunnel at Tsukuba was Ishikawajima-Harima Heavy Industries (IHI). This tunnel is unique among pressurized continuous-flow cryogenic tunnels in that, except for the fan portion of the tunnel, the pressure shell is made of mild steel. This departure from convention was prompted, at least in part, by the existence of an internal insulation system based on a flexible foam material which had been used successfully to insulate liquefied gas containers.[18]

As noted in Reference 19, the use of an internal insulation offers several advantages over external insulation. In general, the advantages include:

(1) savings in coolant due to less thermal mass
(2) shorter times for cool down and warmup
(3) freedom from problems caused by condensation of moisture or liquid oxygen within the insulation due to the pressure shell acting as the vapor barrier
(4) avoidance of problems associated with thermally induced changes in dimensions of the tunnel
(5) possible noise attenuation

In addition to using the flexible foam system to insulate the tunnel, the 10 m^3 concrete LN_2 storage tank used for the 0.5 x 0.5 m low-speed tunnel is also internally insulated with S-foam.

The internal foam insulation has been used in the 0.5 x 0.5 m tunnel at Tsukuba since 1982. However, various problems have been experienced which have necessitated frequent repairs. Consequently, the internal foam insulation is now being removed and replaced with a different insulation.

It was soon discovered that the 10 m^3 concrete storage tank could not be pressurized sufficiently to provide a net positive suction head for the LN_2 pump at low head pressures. This resulted in a relatively large amount of LN_2 being wasted since it could not be pumped into the tunnel. Consequently, the 10 m^3 concrete tank is being replaced with a 20 m^3 stainless steel storage tank which can be pressurized.

These modifications are under way at the time of this writing and are expected to be complete by the end of April, 1985.

A sketch of the 0.5 x 0.5 m low-speed tunnel is shown in Figure 9. The basic specifications for this tunnel are given in Table 9.

Taking advantage of the very wide range of Reynolds number available, the 0.5 x 0.5 m low-speed tunnel has been used with a 50 mm diameter circular cylinder model having a relative roughness, k_s/D, of 10^{-5}. Pressure distributions and vortex shedding were measured from subcritical to transcritical Reynolds numbers (10^5 to 10^7) and Mach Numbers up to 0.3 without changing the experimental arrangement. Drag coefficients were calculated using the measured pressure distributions.[20,21]

Future experiments will also take advantage of the wide range of Reynolds number available in the 0.5 x 0.5 m tunnel. These include determining the effect of surface roughness as well as a splitter plate on the drag and vortex shedding of the circular cylinder, and determining the regularity of the vortex shedding from a square cylinder in the flow.

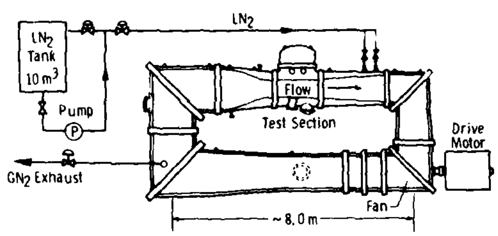

Fig. 9 Sketch of 0.5 x 0.5 m low-speed cryogenic tunnel at Tsukuba.

TABLE 9.- Characteristics of 0.5 x 0.5 m Cryogenic Low-Speed Tunnel at Tsukuba (Japan)

Type........................	closed circuit, fan
Material of construction.....	mostly mild steel
Insulation..................	internal
Cooling.....................	liquid nitrogen
Test gas....................	nitrogen
Test section size (h,w,l)....	0.5 x 0.5 x 1.2 m
Speed range.................	7 - 65 m/s
Mach range..................	up to 0.30
Contraction ratio...........	6.12:1
Stagnation pressure.........	122 - 810 kPa
Stagnation temperature......	118 K - ambient
Running time................	30 min. at max. R
Max. Reynolds number/m.......	200 million
Drive motor.................	450 kW
Fan speed...................	150 - 1500 rpm
LN_2 tank volume.............	20 m^3

4.3 National Defense Academy (NDA)

A cryogenic tunnel is being built for the Department of Aeronautical Engineering of the Japanese National Defense Academy, Yokosuka, Japan. The NDA cryogenic tunnel is to be known as the High Reynolds Number Flow Facility and will be used for basic studies by researchers at the Academy.

The basic specifications for the NDA tunnel are given in Table 10. A sketch of the NDA tunnel is shown in Figure 9. The sketch is a side view which clearly shows the centrifugal compressor at the right. The plenum is mounted on a trolley which is moved to the right to allow access to the test section.

Ishikawajima-Harima Heavy Industries (IHI) has been selected as the contractor for the NDA tunnel. The contract calls for the tunnel to be delivered to NDA in March of 1985.

The NDA tunnel is being designed with 30-cm diameter optical observation windows to allow for flow visualization. Interest has been shown by Professor Yamaguchi and his associates in fitting their cryogenic tunnel with a magnetic suspension and balance system.

TABLE 10.- Characteristics of Cryogenic Tunnel at NDA (Japan)

Type	closed circuit, centrifugal compressor
Material of construction	?
Insulation	external
Cooling	liquid nitrogen
Test gas	nitrogen
Test section size (h,w,l)	0.06 x 0.30 x 1.0 m
Speed range	up to 157 m/s
Mach range	up to 0.80
Contraction ratio	14:1
Stagnation pressure	up to 177 kPa
Stagnation temperature	108 K - ambient
Running time	up to 30 or 40 min
Max. Reynolds number/m	90 million
Drive motor	75 kW
LN_2 tank volume	5 m^3

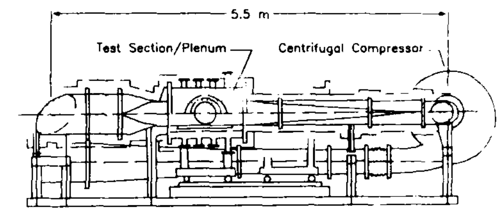

Fig. 10 Sketch of 0.06 x 0.30 m cryogenic tunnel at NDA.

5. SWEDEN

An innovative cryogenic tunnel concept is being studied by Nelander and his colleagues at Aktiebolaget Rollab in Sweden.[22] Shown in Figure 11 are the principal components of a cryogenic wind tunnel based on this new concept.

The main idea behind the concept is the use of a turbine, fed from high-pressure air storage, to drive the fan in a tunnel with a return circuit. The temperature rise in the tunnel due to the fan is balanced by introducing the outlet air from the turbine into the tunnel circuit. This air, of course, has been cooled in the process of expanding through the turbine. The same amount of air introduced into the tunnel circuit from the turbine is dumped from the tunnel through a heat exchanger to the atmosphere or to a vacuum tank, depending on the desired tunnel operating pressure. As can be seen in Figure 11, the air from the high-pressure storage passes through the heat exchanger and is thus cooled before it passes through the turbine.

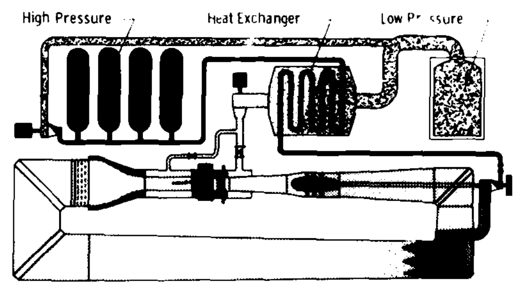

Fig. 11 High Reynolds number transonic wind tunnel based on a new cryogenic cycle. [Ref. 22]

As an example of the application of this concept, Nelander has considered a transonic tunnel having the characteristics given in Table 11.

The compressed air storage envisioned for such a tunnel would contain 36 x 10^3 kg of air at 12 MPa. The power demand on the compressor plant would be on the order of 6 MW.

Details of the operating principal of this new approach to cryogenic tunnels as well as a discussion of the thermodynamic process are given in References 22 and 23.

TABLE 11.- Characteristics of Transonic Cryogenic Tunnel under study at Rollab (Sweden)

Type	closed circuit, intermittent
Material of construction	?
Insulation	?
Cooling	pre-cooled air expanded through turbine
Test gas	air
Test section size (h,w,l)	2.0 x 2.0 x ? m
Mach range	up to 1.4
Contraction ratio	?
Stagnation pressure	50 - 250 kPa
Stagnation temperature	140 - 280 K
Running time	at least 30 s
Frequency of runs	8 times per day
Max. Reynolds number/m	105 million

Also contained in Reference 22 is an economic study comparing this quasi-continuous tunnel to both continuous and blowdown tunnels cooled with liquid nitrogen. Some of the results of the economic study are shown in Figure 12. As can be seen, the quasi-continuous tunnel offers significant savings in operating costs relative to the other concepts.

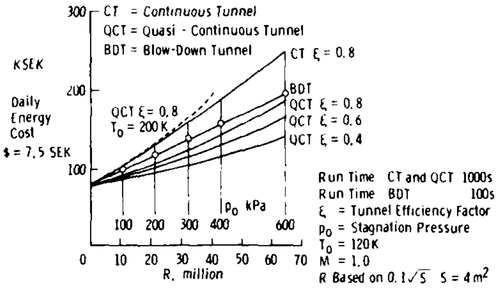

Fig. 12 Cost comparison between three cryogenic wind tunnel concepts. [Ref. 22]

As noted in Reference 22, this entirely new quasi-continuous cryogenic tunnel concept combines the advantage of low power demand and operational flexibility of a blowdown tunnel with the high efficiency and long testing times of a continuous-flow tunnel. Therefore, this new type of cryogenic tunnel should, for a number of applications, provide an attractive alternative to either blowdown or continuous fan-drive for a high Reynolds number transonic tunnel. At this stage in their study of this new tunnel concept, no objections to the theory have been found and all of the practical problems seem to be solvable.

6. UNITED STATES

6.1 Douglas Aircraft Company

The Douglas Aircraft Company, Long Beach, California, has modified existing 1-ft and 4-ft transonic blowdown tunnels for cryogenic operation. A description of some of the modifications to the tunnels required for cryogenic operation is given in Reference 24.

The concept of a blowdown-to-atmosphere cryogenic wind tunnel was successfully proven when the Douglas 1-ft tunnel was first operated at cryogenic temperatures on May 20, 1977. The successful cryogenic operation of the Douglas 1-ft tunnel led to approval to proceed with the program to modify the Douglas 4-ft tunnel for cryogenic operation.

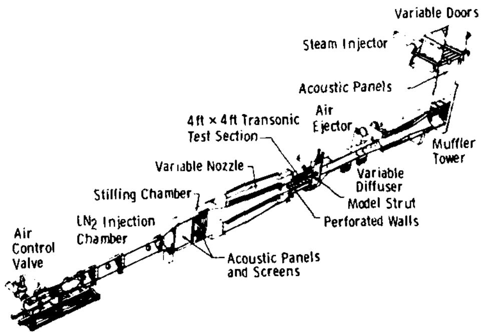

Fig. 13 Sketch of Douglas 4-ft Cryogenic Wind Tunnel (4-CWT). [Ref. 24]

The 1-ft tunnel was subsequently used for a series of tests to determine the effect of nonadiabatic model wall conditions on supercritical airfoil characteristics. Serious effects were demonstrated with only small deviations from adiabatic conditions at test conditions critical to the transonic transport designer.[25]

Capable of achieving Reynolds numbers in excess of 200 million per metre (60 million per foot), the 4-CWT was calibrated and successfully operated at cryogenic temperatures in 1980-81. However, the project was terminated, primarily because of the prohibitive cost of providing a system for model thermal conditioning to the strict tolerances required.

A sketch of the Douglas 4-ft Cryogenic Wind Tunnel (4-CWT) is shown in Figure 13. The basic specifications for the Douglas 4-ft Cryogenic Wind Tunnel were as given in Table 12.

TABLE 12.- Characteristics of 4-ft Cryogenic Wind Tunnel (4-CWT) at Douglas (USA)

Type	blowdown
Material of construction	mostly mild steel; stainless injection chamber
Insulation	internal
Cooling	liquid nitrogen
Test gas	air + nitrogen
Test section size (h,w,l)	1.2 x 1.2 x 3.7 m
Mach range	0.5 - 1.2
Contraction ratio	7.8:1
Stagnation pressure	170 - 480 kPa
Stagnation temperature	100 K - ambient
Running time	45 s at R/m = 135 million; 30 s at R/m = 200 million
Max. Reynolds number/m	200 million
LN_2 tank volume	151 m³

6.2 University of Illinois at Urbana-Champaign

A low-speed fan-driven cryogenic tunnel has been built by Clausing and co-workers in the Department of Mechanical and Industrial Engineering at the University of Illinois

at Urbana-Champaign (UIUC) and extensively used for studies of forced, natural, and combined convective heat transfer under conditions requiring very large values of both Reynolds number and Grashof number.

The building of the cryogenic tunnel at UIUC was prompted by the need to accurately predict combined convective losses from large, high temperature objects such as solar "power tower" receivers where the magnitudes of both the Grashof and Reynolds numbers are large. Clausing and his co-workers proposed that a cryogenic heat transfer tunnel be used to provide an economical method of obtaining the required large values of Grashof and Reynolds numbers with an appropriate and near constant Prandtl number.[26]

The variations of Grashof number and Reynolds number with temperature are shown in Figure 14. As noted in Reference 26, and as can be seen in Figure 14, the use of cryogenic temperatures is a good way to obtain higher Reynolds numbers but an even better way of obtaining higher Grashof numbers. Furthermore, the cryogenic environment virtually eliminates the influence of radiative heat transfer which often causes large errors in natural convection data obtained in conventional facilities.[27] Both the theory and advantages of the cryogenic heat transfer tunnel have been extensively reported[27,28] and will not be included herein.

The basic specifications for the UIUC cryogenic heat transfer tunnel are given in Table 13.

TABLE 13.- Characteristics of Cryogenic Heat Transfer Tunnel at UIUC (USA)

Type	closed circuit, fan
Material of construction	mostly aluminum
Insulation	external, urethane
Cooling	LN_2 heat exchanger with GN_2 injection
Test gas	nitrogen
Test section size (h,w,l)	1.22 x 0.60 x 1.0 m
Speed range	0 - 8 m/s
Contraction ratio	1:1
Stagnation pressure	atmospheric
Stagnation temperature	80 - 300 K
Running time	several minutes
Max. Reynolds number/m	4 million
Drive motor	11.2 kW
Fan speed	0 - 1750 rpm
LN_2 tank volume	1 m^3

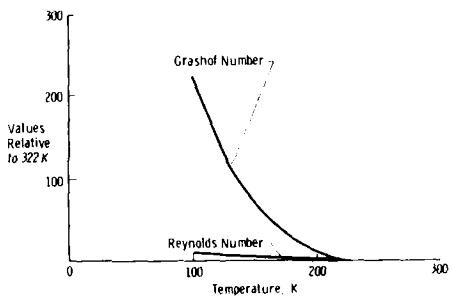

Fig. 14 Effect of temperature on Grashof and Reynolds number. [Ref. 26]

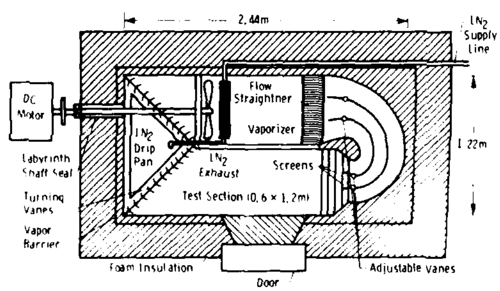

Fig. 15 Cross-sectional view of UIUC Cryogenic Facility. [Ref. 26]

A sketch of the UIUC Cryogenic Facility is shown in Figure 15. The tunnel is cooled by passing liquid nitrogen through a heat exchanger/vaporizer located just downstream of twin drive fans. The resultant gaseous nitrogen from the heat exchanger/vaporizer is vented into the tunnel circuit. In this way, any problems that might arise from incomplete evaporation of liquid nitrogen using direct injection are very effectively avoided. During operation, a slight overpressure is maintained in the tunnel to prevent infiltration of room air. A complete description of the UIUC Cryogenic Facility is given in Reference 29.

The UIUC Cryogenic Facility has been an extremely successful application of the cryogenic tunnel concept. Since first operated on Aug. 17, 1978, it has been extensively used for forced, natural, and combined convective heat transfer research.[30,31] Perhaps the most impressive application of this facility has been its use to determine combined natural and forced convective heat transfer characteristics of the 10 MW facility "Solar One" in Barstow, California, shown in Figure 16. The ability to make such measurements in a relatively small cryogenic wind tunnel provides dramatic demonstration of the usefulness of the simulation laws and the ingenuity of researchers to take advantage of emerging technology to solve long-standing problems.

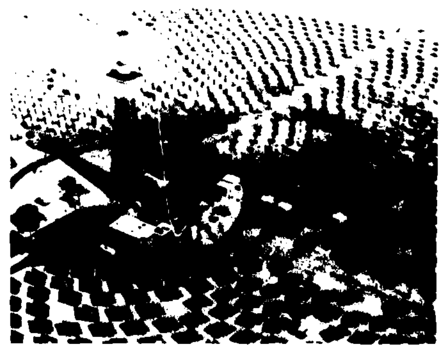

Fig. 16 10 MW "Solar One" at Barstow, Calif.

6.3 NASA Langley

The cryogenic wind tunnel concept was first demonstrated with the construction and successful operation of an atmospheric low-speed tunnel at the NASA Langley Research Center in January 1972.[32] The Langley low-speed cryogenic tunnel started its life as an abandoned 1/24-scale model of the Langley V/STOL tunnel. It was therefore typical of modern low speed wind tunnels in its aerodynamic design and required relatively minor modifications for cryogenic operation. The first true cryogenic operation, that is, stagnation temperature less than about 172 K (-150°F), was on January 31, 1972, when a temperature of 133 K (-220°F) was achieved at 12:05 pm.

Although the Langley low-speed cryogenic tunnel no longer exists as a cryogenic tunnel, having been re-converted to an ambient temperature tunnel, it is briefly described herein for several reasons. First, this low-speed tunnel is typical in both layout and operating principle to the majority of cryogenic tunnels which have been built or proposed. Secondly, it is a tunnel of considerable historical significance, having demonstrated the validity of the cryogenic wind tunnel concept and served as the test bed for the development of operational procedures and testing techniques. Finally, the low-speed tunnel is described in order to demonstrate that not all cryogenic wind tunnels must be expensive and complex. A sketch of this historic tunnel is shown in Figure 17.

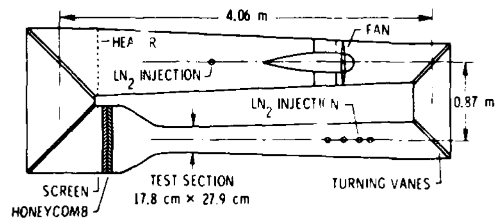

Fig. 17 Sketch of Langley low-speed cryogenic wind tunnel. [Ref. 33]

The basic specifications and operational characteristics for the Langley low-speed cryogenic tunnel were as given in Table 14.

The low-speed tunnel was cooled and the heat of compression added by the fan was removed by spraying liquid nitrogen directly into the tunnel circuit in either of the two locations shown in Figure 17.

The rate of cooling was such that, for example, a temperature of 116 K could be stabilized within 10 minutes of the initiation of cooling from room temperature. The tunnel was operated at temperatures from 333 K to 80 K. Approximately 40 hours of tunnel operation was at cryogenic temperatures, that is, below 172 K. At a reference station in the test section, the test temperature was held to within about ±1 K by automatic on-off control of one or more of the liquid nitrogen injection nozzles. Much closer temperature control was achieved by injecting a slight excess amount of liquid nitrogen and establishing temperature equilibrium at the desired test temperature by manually modulating the heat input from a simple wire-grid electric heater built into the low-speed end of the tunnel. Using this technique, test temperature could be held to within about ±0.2 K.

TABLE 14.- Characteristics of the Low-Speed Cryogenic Tunnel at NASA - Langley (USA)

Type	**closed circuit, fan**
Material of construction	**mostly plywood and plastic**
Insulation	**external**
Cooling	**liquid nitrogen**
Test gas	**nitrogen**
Test section size (h,w,l)	**17.8 x 27.9 x 63.5 cm**
Speed range	**up to 50 m/s**
Mach range	**up to 0.14**
Contraction ratio	**9:1**
Stagnation pressure	**atmospheric**
Stagnation temperature	**80 - 333 K**
Running time	**typically 1 hour**
Max. Reynolds number/m	**20 million**
Drive motor	**7.4 kW**
Fan speed	**up to 3500 rpm**
LN_2 tank volume	**1.14 m^3**

Since the basic tunnel circuit was already built, the low-speed tunnel project was a very low-budget research effort. The cost of materials used to modify and insulate the tunnel circuit was less than $2000 (1971-1972). Materials of construction included wood, plywood, plexiglas, mild and stainless steels, aluminum, brass, copper, and fiberglass reinforced plastic. The fan blades were made of laminated wood.

Viewing ports were provided to allow inspection of key areas of the tunnel circuit including the test section, spray zones, corner vanes, screen section, and contraction section. The viewing ports consisted of either 3 or 4 layers of plexiglas separated by air gaps. Thermal insulation for the remainder of the tunnel circuit was a 7.6 to 10.2 cm layer of expanded polystyrene applied to the outside of the tunnel with a 0.027 cm polyethylene vapor barrier on the outside.

Considerable time was devoted to measuring the temperature distribution around the tunnel circuit since, in the early stages of the project, one of the main concerns was finding an efficient yet simple way to cool the tunnel and still have temperature uniformity, in both time and space, within the test section.

Once adequate operating procedures were worked out, the low-speed cryogenic tunnel was used to experimentally verify, insofar as possible, the validity and practicality of the cryogenic tunnel concept.[33]

Two simple "proof-of-concept" experiments were made in the Langley low-speed cryogenic tunnel. One, using a flat plate with a laminar boundary layer, demonstrated that the true aerodynamic effects of Reynolds number increases are indeed provided when temperatures are reduced to the cryogenic range. The second, using a sharp leading edge delta wing model, verified that conventional strain-gage balance techniques might be used to make force and moment measurements at cryogenic temperatures.

In addition to the two "proof-of-concept" experiments, other experiments, mainly related to developing acceptable cooling techniques and operating procedures, were made in the low-speed cryogenic tunnel.[33] The main conclusions, both aerodynamic and operational, drawn from the experiments as well as the day-to-day operation of the low-speed tunnel are outlined in Table 15.

Table 15.- Major results from the Low-Speed Cryogenic Tunnel at NASA Langley (USA)

Aerodynamic

* **Boundary-layer development with Reynolds number identical for ambient and cryogenic conditions**
* **Drive-power and fan-speed decrease as predicted**

Operational

* **Cooling with liquid nitrogen is practical**
  - **Rapid cooldown**
  - **Automatic temperature control**
  - **Gas stream is clear, dry, and frost free**
* **Use of conventional strain-gage balances is practical**
* **Trouble-free operation of drive motor and fan**

7. CONCLUDING REMARKS

Following the development of the cryogenic wind tunnel at the NASA Langley Research Center in 1972, a large number of cryogenic wind-tunnel projects have been undertaken at various research establishments around the world. The purpose of this lecture has been to describe briefly some of the more significant cryogenic wind-tunnel projects not covered by other lecturers at this Special Course.

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9. ACKNOWLEDGMENTS

The author is grateful to NASA for permission to give this lecture and to his colleagues at the Langley Research center for assisting in its preparation. I am indebted to the following for providing information and material for this lecture: Prof. Han and Mr. Pan of the Chinese Aeronautical Research and Development Center (CARDC), Mr. Takashima of the Japanese National Aerospace Laboratory (NAL), Prof. Adachi of the University of Tsukuba, Professors Nomura and Yamaguchi of the Japanese National Defense Academy (NDA), Prof. Stollery of the College of Aeronautics at Cranfield, Mr. Law of the Royal Aircraft Establishment - Bedford, Dr. Goodyer of the University of Southampton, Mr. Fancher of the Douglas Company, and Professor Clausing of the University of Illinois at Urbana-Champaign (UIUC). I also thank my friend Dr. Wu, recently returned to China from Southampton, England, for providing the translation into English of Mr. Pan's Research Note.

Appendix A
SOURCES OF INFORMATION ON CRYOGENIC WIND TUNNELS

China

2.4 × 2.4 m high Reynolds number Transonic Tunnel at CARDC

Mr Pan Ruikang
China Aerodynamic Research and Development Center
P.O. Box 211
Mianyang
Sichuan

England

Pilot Cryogenic ILPT at Cranfield

Prof. J.L.Stollery
Head, College of Aeronautics
Cranfield Institute of Technology
Cranfield
Bedfordshire MK43 0AL

Telephone: Bedford (0234) 750111
Telex: 825072 CITECHG

Cryogenic Test Duct at RAE-Bedford

Mr R.D.Law
Aerodynamics Department, Bldg 17
Royal Aircraft Establishment
Bedfordshire
MK41 6AE

Telephone: Bedford (0234) 55242, Ext. 7550
Telex: 82117

Cryogenic Low-Speed Tunnel at Southampton

Dr M.J.Goodyer
Department of Aeronautics and Astronautics
The University
Southampton SO9 5NH
Hampshire

Telephone: 44 703 559122, Ext. 2374
Telex: 47661

Cryogenic Free-Piston Expander at Southampton

Dr R.A.East
Department of Aeronautics and Astronautics
The University
Southampton SO9 5NH
Hampshire

Telephone: 44 703 559122, Ext. 2324
Telex: 47661

France

Cryogenic Induction Tunnel T2 at Toulouse

Mr André Mignosi
ONERA CERT – DERAT
BP 4025
31055 Toulouse Cedex

Telephone: 33 61 55-70-44
Telex: 521 596 F

Germany

Cryogenic Ludwieg Tube Tunnel at Göttingen

Dr Gerhard Hefer
DFVLR
Institute for Experimental Fluid Mechanics
Bunsenstrasse 10
3400 Göttingen

Telephone: 49 551-7091
Telex: 96839 dfvgoe-d

The Kryo-Kanal-Köln (KKK)

Dr Gunter Viehweger
DFVLR
Research Center Köln-Porz
Postfach 90 6058
5000 Köln

Telephone: 49 2203 601 2295
Telex: 8 874 410 (dfvw d)

Japan

0.1 × 0.1 m Pilot Transonic Cryogenic Tunnel at NAL
0.6 × 0.6 m Transonic Cryogenic Tunnel under study at NAL

Mr Kazuaki Takashima
Head, Wind Tunnel Instrument Section
Second Aerodynamics Division
National Aerospace Laboratory
1880 Jindaiji Machi, Chofu
Tokyo

0.1 × 0.1 m Low-Speed Cryogenic Tunnel at Tsukuba
0.5 × 0.5 m Low-Speed Cryogenic Tunnel at Tsukuba

Prof. Tsutomu Adachi
Institute of Engineering Mechanics
University of Tsukuba
Sakura, Ibaraki
Japan 300-31

0.06 × 0.30 m Cryogenic Tunnel at NDA

Prof. Yutaka Yamaguchi
Department of Aeronautical Engineering
National Defense Academy
Hashirimizu 1-10-20
Yokosuka, Kanagawa

The Netherlands

The European Transonic Windtunnel, ETW

Mr John Tizard
Technical Group – ETW
c/o National Aerospace Laboratory
P.O. Box 90502
1006 BM Amsterdam

Telephone: 31-20-17-93-25
Telex: 11118

Sweden

Transonic Cryogenic Tunnel under study at Rollab

Mr Curt Nelander
Aktiebolaget Rollab
Jarvstigen 5 Box 7073
S-171 07 Solna

Telephone: 08-85 03-15
Telex: 10598

USA

Douglas 1-ft Cryogenic Wind Tunnel (1-CWT)
Douglas 4-ft Cryogenic Wind Tunnel (4-CWT)

Mr Michael F.Fancher
Douglas Aircraft Company
Mail Code 36-81
3855 Lakewood Boulevard
Long Beach, CA 90846

Telephone: 213 593-5511

Cryogenic Heat Transfer Tunnel at UIUC

Dr A.M.Clausing
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana — Champaign
Urbana, IL 61801

Telephone: 217 333-1176

US National Transonic Facility (NTF) at NASA-Langley

Mr Walter E.Bruce, Jr
Head, NTF Operations Branch
Mail Stop 267
NASA Langley Research Center
Hampton, Virginia 23665

Telephone: 804 865-2701
Telex: 823-405

0.3 m Transonic Cryogenic Tunnel at NASA-Langley

Mr Edward J.Ray
Leader, 0.3-m TCT Research Group
Mail Stop 276
NASA Langley Research Center
Hampton, Virginia 23665

Telephone: 804 865-4395
Telex: 823-405

A-4

Low-Speed Cryogenic Tunnel at NASA-Langley

Dr Robert A.Kilgore
Head, Experimental Techniques Branch
Mail Stop 287
NASA Langley Research Center
Hampton, Virginia 23665

Telephone: 804 865-3713
Telex: 823-405

AD-A161 833 SPECIAL COURSE ON CRYOGENIC TECHNOLOGY FOR WIND TUNNEL TESTING(U) ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT NEUILLY-SUR-SEINE (FRANCE) 4/5

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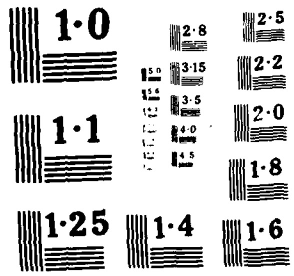
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Appendix B
CRYOGENIC WIND TUNNELS – A SELECTED BIBLIOGRAPHY

This Bibliography with abstracts is reproduced with the permission of NASA from their Technical Memorandum 86346 and Supplement.

INTRODUCTION

This publication, which contains 376 entries, supersedes three previous cryogenic wind tunnel bibliographies: NASA TM-80168 (Oct. 1979), Supplement to NASA TM-80168. (May 1980), and NASA TM-84474 (Sept. 1982). This updated version cites 109 additional documents.

For the purpose of this bibliography, a cryogenic wind tunnel is defined as one which operates with test gas stagnation temperatures below 150 K. The intent is to list publications that might be useful to persons interested in building or using a cryogenic wind tunnel. Also included are some publications of historical interest that are directly related to key events in the evolution of the cryogenic wind tunnel. The arrangement is chronological by date of publication in the case of reports and by presentation in the case of papers. Translations, if available, are usually placed immediately after the original language document.

Considerable effort has been made to include the relevant literature. Some relevant papers have not been included because they are not generally available. It is hoped that these papers will eventually be published in the open literature, where their contribution will be available to all.

There are several books, papers, and bibliographies that, although not dealing directly with cryogenic wind tunnels, have been found to be useful sources of information. These items have been added to the end of this bibliography as citations A1 through A11.

Indexes by author, source, and subject are provided to increase the usefulness of this compilation.

In many cases, abstracts used are from the NASA announcement bulletins "Scientific and Technical Aerospace Reports" (STAR) and "International Aerospace Abstracts" (IAA). In other cases, authors' abstracts were used. License was taken to modify or shorten abstracts, using only parts pertinent to the subject of the bibliography. If it is known that an item has appeared in several forms, mention is made of this fact. Accession numbers, report numbers, and other identifying information are included in the citations in order to facilitate the filling of requests for specific items.

When requesting material from your library or other source, it is advisable to include the complete citation. The abstract may be omitted.

ISSN—ISSN is an acronym for International Standard Serial Number, an internationally accepted code for the identification of serial publications; it is precise, concise, unique, and unambiguous.

ISBN—ISBN is an acronym for International Standard Book Number, a number which is given to every book or edition of a book before publication to identify the publisher, the title, the edition, and volume number.

Availability sources of the different types of materials are given below:

AVAILABILITY

Acquisition Number	Type of Material	Where Obtained
AXX-XXXXX Example: A75-25583	AIAA papers and published literature available from AIAA or in journals, conferences, etc., as indicated	American Institute of Aeronautics and Astronautics Technical Information Service 555 West 57th Street, 12th Floor New York, NY 10019
NXX-XXXXX Example: N67-37604	Report literature having no distribution limitation	National Technical Information Service (NTIS) 5285 Port Royal Road Springfield, VA 22161
XXX-XXXXX Example: X72-76040	Report literature having some type of distribution limitation	NASA Scientific and Technical Information Facility (STIF) P.O. Box 8757 B.W.I. Airport, MD 21240
AD Numbers	Report literature with or without distribution limitation	Defense Technical Information Center Cameron Station Alexandria, VA 22314

AVAILABILITY

Acquisition Number	Type of Material	Where Obtained
Order number (when given)	Theses	University Microfilms A Xerox Company 300 North Zeeb Road Ann Arbor, MI 48106

For any other type of material, contact your library or the NASA Scientific and Technical Information Facility (see address above), and include any *information* given.

A "#" after an acquisition number indicates that the document is *also available* in microfiche form.

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This is a 2½ page short version (abstract), in French, of NACA TN-52. This was presented for W. Margoulis by M. L. Lecornu.

*NACA, Paris Office

2 *Margoulis, W. **A New Method of Testing Models in Wind Tunnels.** NACA *TN*-52, Aug. 1921.

This paper discusses the use of gases other than air and the use of *nonambient temperatures and pressures* as ways of *increasing* test Reynolds number and reducing capital cost and drive power requirements for low-speed wind tunnels. The use of carbonic acid gas (CO_2) is examined in detail.

*NACA, *Paris Office*

3 Smelt, R. **Power Economy in High-Speed Wind Tunnels by Choice of Working Fluid and Temperature.** British R.A.E. Rep. no. *Aero 2081*, Aug. 1945

The power required to operate a high-speed wind tunnel at fixed Mach number, Reynolds number, and pressure can be greatly reduced if instead of air at normal temperatures, other fluids or low *temperatures are employed*. If operation at normal temperatures is desired, best power economy is obtained by using certain fluorine compounds of high molecular weight. The value of γ for all these substances is low—about 1.15, compared with 1.4 for air. No substance is known which will permit substantial power reduction at normal temperature with $\gamma=1.4$. If $\gamma=1.4$ is essential—nothing definite can be said on this point—then power economy is best achieved by refrigeration. This is permissible down to a definite limiting temperature. For air the limit is 126° R, and the power there is only *7% of that at normal temperature*. Use of nitrogen permits an operating temperature of 108° R, and the power required is 3.8% of that for air at normal temperatures.

4 Pankhurst, R. C.; and Holder, D. W.: **Power Economy by Reduction of Stagnation Temperature.** Wind Tunnel Technique, Sir Isaac Pitman and Sons, Ltd., London, 1952, pp. 45-47.

The advantages with respect to power economy of a reduction in stagnation temperature are noted. "Since refrigeration does not involve an increase in the stresses in the model, nor a departure from the conditions of dynamic similarity, it might appear to be a promising method of power economy. The practical difficulties involved would be considerable."

5 *Fowler, H. S., and *Rush, C. K.: **Centrifugal Compressors—A Brief History and a Description of Some Current Research.** Quarterly Bulletin of the Division of Mechanical Engineering, National Research Council of Canada, Oct.-Dec. 1962, pp. 35-54. Also, Canadian Aeronautics and Space Journal, Jan. 1964, pp. 7-12.

N63-13998

A brief account of the historical development of the centrifugal compressor shows a continued improvement until a peak was reached about 1955. After some years of neglect, interest is now reawakening in this field. Following a very short review of some aspects of compressor theory, two novel experimental approaches *to the investigation of flow and efficiency in the compressor are* described. The test rigs being used in these investigations in the Mechanical Engineering Division of NRC are illustrated. One of these rigs, the heat exchanger of which is cooled with liquid nitrogen, is of especial interest.

*National Research Council of Canada, Ottawa, ON, K1A, OR6, Canada

6 *Rush, C. K.: **A Low Temperature Centrifugal Compressor Test Rig** (Mechanical Engineering Report). National Research Council of Canada Rep. MD-48; NRC-7776, Nov. 1963, 57 pp.

N64-25199

An examination of the requirements for dynamic similarity in centrifugal compressors demonstrates the possible advantages of *using air at temperatures down to 100 K. A test rig capable of* operating at low temperature is described. Test results for inlet conditions, ranging from room temperature to 125 K are presented. The predicted advantages of operating at low temperature are confirmed. However, the desired result that the performance should be identical at four different conditions of dynamic similarity was not achieved, although the differences are relatively small. Further examination of the results suggests that the differences are due to changes in geometry with changes in the test rig internal pressure.

*National Research Council of Canada, Ottawa, ON, K1A, OR6, Canada

7 *Goodyer, M. J.; and **Kilgore, R. A.: **The High Reynolds Number Cryogenic Wind Tunnel.** AIAA paper 72-995, 7th Aerodynamic Testing Conference, Palo Alto, Calif., Sept. 13-15, 1972. Also, AIAA Journal, vol. 11, no. 5, May 1973, pp. 613-619.

AIAA-72-995 A72-41581#

Theoretical considerations indicate that cooling the wind-tunnel test gas to cryogenic temperatures will provide a large increase in test Reynolds number with no increase in dynamic pressure while reducing the tunnel drive-power requirements. Studies have been made to determine the expected variations of Reynolds number and other parameters over wide ranges of Mach number, pressure, and temperature with due regard to avoiding liquefaction and adverse real-gas effects. Practical operational *procedures have been developed in a low-speed prototype cryo*genic wind tunnel. Aerodynamic experiments in the facility have demonstrated the theoretically predicted variations in Reynolds number and drive power. Force and moment measurements on a wing model mounted on a water-jacketed strain-gage sting balance have demonstrated the feasibility of operation of such balances in a cryogenic environment.

*The University, Southampton SO9 5NH, Hampshire, U.K.

**NASA, Langley Research Center, Hampton, VA, 23665

8 *Lin, Shih-Chun **An Experimental Study of Gasdynamical *Turbulence.*** *California Univ., San Diego.* Ph. D. Thesis, 1972. 230 pp. (Available Univ. Microfims, Order No. 72-24634).

N73-19280

A nearly homogenous grid turbulence field with large-amplitude temperature fluctuations is investigated experimentally. In order to generate a nearly homogenous flow field with large temperature fluctuations in the *laboratory, a 21' × 21' variable density*, subsonic wind tunnel with the capability of generating Reynolds number per inch up to 3.5×10^4 when operated at ambient temperatures and up to 3.0×10^5 when operated at 100 K by the direct injection of liquid nitrogen has been designed and developed. The

details of the design and the discussion of the tunnel performance ceration has been postponed.

*University of California, San Diego, CA, 92112

9 *Jacobsen, R. T., *Stewart, R. B.; *McCarty, R. D., and *Hanley, H. J. M.: **Thermophysical Properties of Nitrogen from the Fusion Line to 3500 R (1944 K) for Pressures to 150,000 psia (10342 × 10⁵ N/m²).** National Bureau of Standards, NBS TN-648, Dec. 1973. 162 pp. (Available from U. S. Government Printing Office, Washington, DC 20402. Catalog #C13.46:648.)

N74-17637#

Tables of thermophysical properties of nitrogen are presented for temperatures from the fusion line to 3500 R for pressures to 3000 psia, and from the fusion line to 1500 R for pressures above 3000 psia to 150,000 psia. The tables include values of entropy, enthalpy, internal energy, density, specific volume, velocity of sound, specific heats (C_v and C_p), thermal conductivity, viscosity, thermal diffusivity, Prandtl number, and the dielectric constant for selected isobars. Additional tables are included for values of $(\partial P/\partial V)_T$, $(\partial P/\partial T)_\rho$, $V(\partial H/\partial V)_\rho$, $(\partial P/\partial U)_v$, $V(\partial P/\partial V)_T$, and $(\partial V/\partial T)_p$, which have special utility in heat transfer calculations. Tables of selected isobars for the liquid and vapor phases, and for the saturated vapor and saturated liquid are included. An equation of state is presented for liquid and gaseous nitrogen for the temperature and pressure ranges of these tables. In the determination of the equation of state, all of the P-ρ-T (pressure-density-temperature) data available from the published literature were reviewed, and appropriate corrections were made to bring experimental temperatures into accord with the International Practical Temperature Scale of 1968. The coefficients of the equation of state were determined by a weighted least squares fit to selected P-ρ-T data and simultaneously to C_v data determined by corresponding states analysis from oxygen data, and to data which defined the phase equilibrium criteria for the saturated liquid and saturated vapor. A vapor pressure equation, melting curve equation, and an equation to represent the ideal gas heat capacity of nitrogen are also presented. The equation of state is estimated to be accurate to within 0.5 percent in the liquid region, to within 0.1 percent for supercritical isotherms up to 15,000 psia, and to within 0.3 percent from 15,000 to 150,000 psia. The vapor pressure equation is accurate to within ±0.01 K between the triple point and the critical point.

*National Bureau of Standards Boulder Labs, Boulder, CO, 80302

Contract NASA-MSC-T-1813A

10 *Kilgore, R. A.; *Adcock, J. B.; and *Ray, E. J.: **Flight Simulation Characteristics of the Langley High Reynolds Number Cryogenic Transonic Tunnel.** 12th Aerospace Sciences Meeting, Washington, DC, Jan. 30-Feb. 1, 1974. 9 pp.

AIAA Paper 74-80 A74-20761#

The characteristics of the Langley 34 cm (13.5 in.) pilot cryogenic transonic pressure tunnel are described, and the results of initial tunnel operation are presented. Tests of a two-dimensional airfoil at a Mach number of 0.85 show identical pressure distributions for a chord Reynolds number of 8,600,000 obtained first at a stagnation pressure of 4.91 atmospheres at a stagnation temperature of +120° F and then at a stagnation pressure of 1.19 atmospheres at a stagnation temperature of -250° F.

*NASA, Langley Research Center, Hampton, VA, 23665

11 *Kilgore, Robert Ashworth: **The Cryogenic Wind Tunnel for High Reynolds Number Testing.** Southampton Univ., U. K. Ph.D. Thesis. Feb. 1974. NASA TM X-70207, 230 pp. Available NTIS.

N74-27722#

Experiments performed at the NASA Langley Research Center in a cryogenic low-speed continuous-flow tunnel and in a cryogenic transonic continuous-flow pressure tunnel have demonstrated the predicted changes in Reynolds number, drive power, and fan speed with temperature, while operating with nitrogen as the test gas. The experiments have also demonstrated that cooling to cryogenic temperatures by spraying liquid nitrogen directly into the tunnel circuit is practical and that tunnel temperature can be controlled within very close limits. Whereas most types of wind tunnels could operate with advantage at cryogenic temperatures, the continuous-flow fan-driven tunnel is particularly well suited to take full advantage of operating at these temperatures. A continuous-flow fan-driven cryogenic tunnel to satisfy current requirements for test Reynolds number can be constructed and operated using existing techniques. Both capital and operating costs appear acceptable.

*NASA, Langley Research Center, Hampton, VA, 23665

12 *Adcock, J. B.: **The Cryogenic Wind Tunnel Concept.** (Presented during the House Authorization Subcomittee Hearings on the OAST FY '75 Budget). NASA TM-80504, Mar. 1974. 13 pp. (NASA only).

X80-70012#

*NASA, Langley Research Center, Hampton, VA 23665

13 *Wilson, John F.; *Ware, George D.; and *Ramsey, James W., Jr.: **Pilot Cryo Tunnel: Attachments, Seals, and Insulation.** Presented at the ASCE National Structural Meeting, Cincinnati, Ohio, April 22-26, 1974. NASA TM-80509, 1974, 30 pp.

N79-30244#

This paper describes tests performed in evaluation of flange attachments, seals, and the structural support insulation for a pilot cryogenic wind tunnel. The overall dimensions of the pilot tunnel are 9.9 m long, 3.7 m high, and 1.2 m maximum diameter, with a 0.34 m octagonal test section, and a 12/1 contraction ratio. The fan-driven closed circuit tunnel at the NASA Langley Research Center was designed for operation at cryogenic nitrogen temperature and required knowledge of material behavior and performance in addition to that available from the literature. The design conditions for the tunnel are pressures up to 5 atmospheres (507 kPa) and temperatures from 78 K (-320° F) to 322 K (+120° F). The cold temperature, in conjunction with the pressure, required tests and studies in the following areas: Compatible bolting, adequate sealing, and effective insulating materials.

*NASA, Langley Research Center, Hampton, VA, 23665

14 *Zapata, Ricardo N.; *Humphris, Robert R.; and *Henderson, Karl C.: **Experimental Feasibility Study of the Application of Magnetic Suspension Techniques to Large-Scale Aerodynamic Test Facilities.** 8th AIAA Aerodynamic Testing Conference, Md., July 8-10, 1974. 11 pp. This was also published as NASA CR-146761, 1975, 10 pp.

AIAA Paper 74-615 N80-11102#
A74-35383#

Based on the premises that magnetic suspension techniques can play a useful role in large-scale aerodynamic testing and that superconductor technology offers the only practical hope for building large-scale magnetic suspensions, an all-superconductor three-component magnetic suspension and balance facility was built as a prototype and was tested successfully. Quantitative extrapolations of design and performance characteristics of this prototype system to larger systems compatible with existing and planned high Reynolds number facilities have been made and show that this experi-

mental technique should be particularly attractive when used in conjunction with large cryogenic wind tunnels.

Note: Similar information is contained in AGARD-CP-174 (N76-25213#), and in NASA CR-2565 (N75-28025).

*University of Virginia, Charlottesville, VA, 22901

NASA Grants NGR-47-005-029; NGR-47-005-110; NGR-47-005-112; and NSG-1010.

15 *Ray, Edward J.; *Kilgore, Robert A.; *Adcock, Jerry B.; and *Davenport, Edwin E.: **Test Results From the Langley High Reynolds Number Cryogenic Transonic Tunnel.** 8th Aerodynamic Testing Conference, Bethesda, Md., July 8-10, 1974. Also, Journal of Aircraft, vol. 12, no. 6, June 1975, pp. 539-544.

AIAA Paper 74-631 A74-35395#

NASA has recently developed and proof tested a pilot cryogenic transonic pressure tunnel. In addition to providing an attractive method for obtaining high Reynolds number results at moderate aerodynamic loadings and tunnel power, this unique facility enables the independent determination of the effects of Reynolds number, Mach number, and aeroelasticity. The proof-of-concept experimental and theoretical studies are briefly reviewed. Experimental results are included which indicate pressure distributions for a two-dimensional airfoil and strain-gage balance characteristics for a three-dimensional delta wing model.

*NASA, Langley Research Center, Hampton, VA, 23665

16 *Polhamus, E.C.; *Kilgore, R.A.; *Adcock, J.B.; and *Ray, E.J.: **The Langley Cryogenic High Reynolds Number Wind-Tunnel Program.** Astronautics and Aeronautics, vol. 12, no. 10, Oct. 1974, pp. 30-40.

A74-45305#

A pilot version of a new type of transonic tunnel was placed in operation in the fall of 1973. In the tunnel the cryogenic method is used to obtain a high Reynolds number. The cryogenic concept employs low temperatures to increase the Reynolds number through reducing the viscous forces rather than increasing the inertia forces. The cryogenic approach offers the desired Reynolds-number increase with no increase in dynamic pressure, and therefore no increase in model loads. A series of aerodynamic experiments have been made in the pilot tunnel to confirm the cryogenic concept at transonic speeds. A brief description is given of the project for a large tunnel which has evolved from the investigations.

*NASA, Langley Research Center, Hampton, VA, 23665

17 *Kilgore, Robert A.; **Goodyer, Michael J.; *Adcock, Jerry B.; and *Davenport, Edwin E.: **The Cryogenic Wind Tunnel Concept for High Reynolds Number Testing.** NASA TN-D-7762, Nov. 1974, 96 pp.

N75-12000#

Theoretical considerations indicate that cooling the wind-tunnel test gas to cryogenic temperatures will provide a large increase in Reynolds number with no increase in dynamic pressure while reducing the tunnel drive-power requirements. Studies were made to determine the expected variations of Reynolds number and other parameters over wide ranges of Mach number, pressure, and temperature, with due regard to avoiding liquefaction. Practical operational procedures were developed in a low-speed cryogenic tunnel. Aerodynamic experiments in the facility demonstrated the theoretically predicted variations in Reynolds number and drive power. The continuous-flow-fan-driven tunnel is shown to be particularly well suited to take full advantage of operating at cryogenic temperatures.

*NASA, Langley Research Center, Hampton, VA, 23665
**The University, Southampton SO9 5NH, Hampshire, U.K.

18 *Kilgore, Robert A.; *Adcock, Jerry B.; and *Ray, Edward J.: **Simulation of Flight Test Conditions in the Langley Pilot Transonic Cryogenic Tunnel.** NASA TN-7811, Dec. 1974, 24 pp.

N75-12001#

The theory and advantages of the cryogenic tunnel concept are briefly reviewed. The unique ability to vary temperature independently of pressure and Mach number allows, in addition to large reductions in model loads and tunnel power, the independent determination of Reynolds number, Mach number, and aeroelastic effects on the aerodynamic characteristics of the model. Various combinations of Reynolds number and dynamic pressure are established to represent accurately flight variations of aeroelastic deformation with altitude changes. The consequences of the thermal and caloric imperfections of the test gas under cryogenic conditions were examined and found to be insignificant for operating pressures up to 5 atm. The characteristics of the Langley pilot transonic cryogenic tunnel are described and the results of initial tunnel operation are presented. Tests of a two-dimensional airfoil at a Mach number of 0.85 show identical pressure distributions for a chord Reynolds number of 8,600,000 obtained first at a stagnation pressure of 4.91 atm at a stagnation temperature of 322.0 K and then at a stagnation pressure of 1.19 atm at a stagnation temperature of 116.5 K.

*NASA, Langley Research Center, Hampton, VA, 23665

19 *Reubush, David E.: **The Effect of Reynolds Number on Boattail Drag.** AIAA 13th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 20-22, 1975. 7 pp.

AIAA Paper 75-63 A75-18286#

An investigation has been conducted in the Langley pilot transonic cryogenic tunnel to determine the effects of varying Reynolds number on boattail drag at subsonic speeds. Six boattailed cone-cylinder nacelle models were tested with the jet exhaust simulated by a cylindrical sting. Reynolds number was varied from about 2.6 million to 132 million by changing model length and unit Reynolds number. Boattail pressure coefficient distributions show that increasing Reynolds number tends to make the pressure coefficients in the expansion region more negative and the pressure coefficients in the recompression region more positive. These two effects were compensating and as a result there was little or no effect of Reynolds number on the pressure drag of the isolated boattails.

*NASA, Langley Research Center, Hampton, VA, 23665

20 *Adcock, Jerry B.; *Kilgore, Robert A.; and *Ray, Edward J.: **Cryogenic Nitrogen as a Transonic Wind-Tunnel Test Gas.** AIAA 13th Aerospace Sciences Meeting, Pasadena, Calif. Jan. 20-22, 1975. 9 pp.

AIAA Paper 75-143 A75-18341#

The test gas for the Langley Pilot Transonic Cryogenic Tunnel is nitrogen. Results from analytical and experimental studies that have verified cryogenic nitrogen as an acceptable test gas are reviewed. Real-gas isentropic and normal-shock flow solutions for nitrogen are compared to the ideal diatomic gas solutions. Experimental data demonstrate that for temperatures above the liquefaction boundaries there are no significant real-gas effects on two-dimensional airfoil pressure distributions. Results of studies to

determine the minimum operating temperatures while avoiding appreciable effects due to liquefaction are included.

*NASA, Langley Research Center, Hampton, VA, 23665

21 *Ray, Edward J., *Kilgore, Robert A., *Adcock, Jerry B.; and *Davenport, Edwin E. **Analysis of Validation Tests of the Langley Pilot Transonic Cryogenic Tunnel.** NASA TN-D-7828, Feb. 1975 22 pp.

N75-16569#

A pilot transonic cryogenic pressure tunnel has recently been developed and proof tested at the NASA Langley Research Center. In addition to providing an attractive method for obtaining high Reynolds number results at moderate aerodynamic loading and tunnel power, this unique tunnel allows the independent determination of the effects of Reynolds number, Mach number, and dynamic pressure (aeroelasticity) on the aerodynamic characteristics of the model under test. The proof of concept experimental and theoretical studies are briefly reviewed. Experimental results obtained on both two- and three-dimensional models have substantiated that cryogenic test conditions can be set accurately and that cryogenic gaseous nitrogen is a valid test medium.

*NASA, Langley Research Center, Hampton, VA, 23665

22 *Osborne, B. P., Jr.; and **Nicks, O. W. (Co-chairmen): **National Transonic Facility: Report of the 1974 National Aeronautical Facilities Subpanel to the Aeronautics Panel, AACB.** Aeronautics and Astronautics Coordinating Board, Washington, DC, May 1975. 63 pp.

N79-79161#

At its 69th meeting, the Aeronautics and Astronautics Coordinating Board (AACB) authorized the Aeronautics Panel to proceed with a review of national aeronautics facilities. The specific Terms of Reference are set forth in Attachment A. The members of the 1974 National Aeronautics Facilities Subpanel constituted by the Aeronautics Panel are identified in Attachment B. Prior to the first meeting of the subpanel, the Cochairmen of the AACB Aeronautics Panel agreed to modify the Terms of Reference to eliminate consideration by this subpanel of the USAF Aeropropulsion System Test Facility (ASTF) and the NASA/Ames 40 × 80 foot tunnel modifications. Hence, this report is concerned only with a review of the High Reynolds Number Tunnel (HIRT) and the Transonic Research Tunnel (TRT) and related requirements.

*U.S. Department of Defense, Arlington, VA, 20301

**NASA, Langley Research Center, Hampton, VA, 23665

23 *Kilgore, Robert A.; and *Kuhn, R. E.: **Recent Progress on New Facilities at the NASA Langley Research Center.** In AGARD CP-187, "Flight/Ground Testing Facilities Correlation," pp. 2-1 through 2-14. Presented at 46th Meeting of the Flight Mechanics Panel, Valloire, France, 9-13 June, 1975.

N76-25269#

A new fan-driven high Reynolds number transonic cryogenic tunnel is being planned for the United States. This tunnel, to be known as the National Transonic Facility, will take full advantage of the cryogenic concept to provide an order of magnitude increase in Reynolds number capability over existing tunnels. Based on theoretical studies and experience with the Langley 0.3-m Transonic Cryogenic Tunnel, the cryogenic concept has been shown to offer many advantages with respect to the attainment of full-scale Reynolds number at reasonable levels of dynamic pressure in a ground-based facility. The unique modes of operation which are available only in a cryogenic tunnel make possible for the first time the separation of Mach number, Reynolds number, and aeroelastic effects. By reducing the drive power requirements to a level where a conventional fan drive system may be used, the cryogenic concept makes possible a tunnel with high productivity and run times sufficiently long to allow for all types of tests at reduced capital costs and, for equal amounts of testing, reduced total energy consumption in comparison with other tunnel concepts.

*NASA, Langley Research Center, Hampton, VA, 23665

24 *Hall, Robert M. **Preliminary Study of the Minimum Temperatures for Valid Testing in a Cryogenic Wind Tunnel.** NASA TM X-72700, Aug. 1975 125 pp.

N75-28078#

The minimum operating temperature which avoids real-gas effects, such as condensation, was determined at a Mach number of 0.85 for a 0.137-m NACA 0012-64 airfoil mounted in the Langley 0.3-m Transonic Cryogenic Tunnel. For temperatures within 5 K of reservoir saturation and total pressures from 1.2 to 4.5 atm, the pressure distributions over the airfoil are not altered by real-gas effects. This ability to test at total temperatures below those which avoid saturation over the airfoil allows an increase in Reynolds number capability of at least 17 percent for a constant tunnel total pressure. Similarly, 17 percent less total pressure is required to obtain a given Reynolds number.

*NASA, Langley Research Center, Hampton, VA, 23665

25 *Mabey, Dennis G.: **Some Remarks on the Design of Transonic Tunnels With Low Levels of Flow Unsteadiness.** NASA CR-2722, Aug. 1976. 19 pp. (Based on a lecture given at Langley on Sept. 15, 1975.)

N79-25039#

Flow unsteadiness in wind tunnels is defined and its importance for aerodynamic measurements outlined. The principal sources of flow unsteadiness in the circuit of a transonic wind tunnel are enumerated. Care must be taken to avoid flow separations, acoustic resonances, and large scale turbulence. Some problems discussed are the elimination of diffuser separations, the aerodynamic design of coolers and the unsteadiness generated in ventilated working sections (both slotted and perforated).

*Royal Aircraft Establishment, Bedford MK41 6AE, U.K.

26 *Mabey, Dennis G.: **Some Remarks on Dynamic Aeroelastic Model Tests in Cryogenic Wind Tunnels.** Presented at NASA, Langley Research Center, Sept. 1975. NASA CR-145029 39 pp.

N76-78044

The application of cryogenic wind tunnels to dynamic aeroelastic model tests is the subject of this informal lecture and discussion. Emphasis is placed on buffet testing with a description of two semi-span models that could be tested in the Langley 0.3-m Transonic Cryogenic Tunnel to develop a buffet testing technique suitable for use at cryogenic temperatures.

*Royal Aircraft Establishment, Bedford MK41 6AE, U.K.

27 *Reubush, David E.: **The Effect of Reynolds Number on the Boattail Drag of Two Wing-Body Configurations.** 11th AIAA and SAE Propulsion Conference, Anaheim, Calif., Sept. 29-Oct. 1, 1975. 8 pp.

AIAA Paper 75-1294 A75-45681#

An investigation has been conducted in the Langley 0.3-m Transonic Cryogenic Tunnel to determine the effects of varying Reynolds number on the boattail drag of wing-body configurations

at subsonic speeds. Two boattailed cone-cylinder nacelle models were tested with a 60° delta wing at an angle of attack of 0°. Reynolds number, based on model length, was varied from about 2.5 million to 67 million. Even though the presence of the wing had large effects on the boattail pressure coefficients, the results of this investigation were similar to those previously found for a series of isolated boattails. Boattail pressure coefficients in the expansion region became more negative with increasing Reynolds number, while those in the recompression region became more positive. These two effects were compensating, and as a result, there was virtually no effect of Reynolds number on boattail pressure drag.

*NASA, Langley Research Center, Hampton, VA. 23665

28 *Hall, Robert M. and *Ray, Edward J. **Investigation of Minimum Operating Temperatures for Cryogenic Wind Tunnels.** AIAA 14th Aerospace Sciences Meeting, Washington, DC, Jan. 26-28, 1976. Also, Journal of Aircraft, vol. 14, no. 6, June 1977, pp. 560-564.

AIAA Paper 76-89 A76-18781#

Total temperatures corresponding to the onset of condensation effects were determined for flow over a 0.137-m NACA 0012-64 airfoil mounted in the Langley 0.3-m Transonic Cryogenic Tunnel. Tests were carried out at a total pressure range from 1.2 to 4.5 atm and at free-stream Mach numbers of 0.75, 0.85, and 0.95. No condensation effects were found to occur until total temperatures were below those associated with free-stream saturation. Significant increases in Reynolds number may apparently be obtained by operation at temperatures below those associated with local saturation over the airfoil but above those where effects first occur. For the 0.85 and 0.95 Mach numbers the increase in Reynolds number was at least 15 percent over those achieved at local saturation conditions for the same pressure range.

*NASA, Langley Research Center, Hampton, VA. 23665

29 *Ludwieg, H.; *Grauer-Carstensen, H.; and *Lorenz-Meyer, W. **The Ludwieg Tube—A Proposal for a High Reynolds Number Transonic Wind Tunnel.** In AGARD-CP-174, Wind Tunnel Design and Testing Technology, March 1976, pp. 3-1 through 3-11.

N76-25216

After a brief review of the historical development of the Large European High Reynolds Number Tunnel (LEHRT) and its specifications, the advantages and flexibility of a Ludwieg tube drive system are outlined. Special emphasis is given to the development of the boundary layer in the charge tube and its influence on the flow quality in the test section. The theoretical predictions of boundary layer growth are confirmed by experimental results. An improved prediction method for the turbulence in the test section is given. Means to affect the turbulence in order to meet the LEHRT requirements are outlined. After a short review of the development of cost estimates some options are discussed which promise significant reduction in construction costs without impairing performance. These solutions are the application of prestressed concrete for large parts of the construction, lowering the stagnation temperature by an amount of approximately 50° C, and operation at cryogenic temperatures.

*DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

30 *Kilgore, Robert A., *Adcock, Jerry B.; and *Ray, Edward J.: **The Cryogenic Transonic Wind Tunnel for High Reynolds Number Research.** In AGARD-CP-174, Wind Tunnel Design and Testing Technology, Mar. 1976, pp. 1-1 through 1-20.

N76-25214

Based on theoretical studies and experience with a low speed cryogenic tunnel and with a transonic cryogenic tunnel, the cryogenic wind tunnel concept has been shown to offer many advantages with respect to the attainment of full scale Reynolds number at reasonable levels of dynamic pressure in a ground based facility. The unique modes of operation available in a pressurized cryogenic tunnel make possible for the first time the separation of Mach number, Reynolds number, and aeroelastic effects.

*NASA, Langley Research Center, Hampton, VA. 23665

31 *Haut, Richard C.; and **Adcock, Jerry B.: **Steady Normal Shock Wave Solution Tables of Parahydrogen for Total Temperatures from 30 K to 290 K and for Total Pressure from 1 Atm to 10 Atm.** NASA TM X-73899, April 1976. 100 pp.

N76-23518#

The steady normal shock wave solutions of parahydrogen at various total pressures and total temperatures were numerically determined by iterating the upstream Mach number and by using a modified interval halving technique. The results obtained are compared with the ideal diatomic gas values and are presented in tabulated form.

*Old Dominion University, Norfolk, VA. 23508

**NASA, Langley Research Center, Hampton, VA. 23665

32 *Haut, Richard C.; and **Adcock, Jerry B.: **Tables of Isentropic Expansions of Parahydrogen and Related Transport Properties for Total Temperatures from 25 K to 300 K and for Total Pressures from 1 Atm to 10 Atm.** NASA TM-X-72826, April 1976. 93 pp.

N76-22489#

The isentropic expansions of parahydrogen at various total pressures and total temperatures were numerically determined by iterating Mach number and by using a modified interval halving method. The calculated isentropic values and related properties are presented in tabulated form.

*Old Dominion University, Norfolk, VA. 23508

**NASA, Langley Research Center, Hampton, VA. 23665

33 *Reubush, David E.; and *Putnam, Lawrence E.: **An Experimental and Analytical Investigation of Effect on Isolated Boattail Drag of Varying Reynolds Numbers up to 130,000,000.** NASA TN-D-8210, May 1976. 85 pp.

N76-23171#

An investigation was conducted to determine whether large Reynolds number effects occur on isolated boattails. The investigation included an analytical study and tests in the Langley 0.3-m Transonic Cryogenic Tunnel. This investigation was conducted at an angle of attack of 0° at Mach numbers from 0.6 to 0.9 for Reynolds numbers up to 130×10^6. Results indicate that as the Reynolds number was increased, the boattail static pressure coefficients in the expansion region of the boattail became more negative whereas those in the recompression region became more positive. These two trends were compensating and, as a result, there was only a small effect (if any) of Reynolds number on boattail pressure drag.

*NASA, Langley Research Center, Hampton, VA. 23665

34 *Rao, D.M.: **Wind Tunnel Design Studies.** Final Report (June '75 through May '76). Old Dominion Univ., TR-76-T11, NASA CR-148149, May 1976. 31 pp.

N76-25156#

This report described work performed at Langley Research Center in support of the National Transonic Facility Project Office.

The report is in three parts: estimation of aerodynamic losses in the tunnel circuit, 2nd-turn model studies, and proposed circuit modification for LN_2 economy and shell cost savings. The report emphasizes the basic motivation behind the problems studied, and gives the main results and conclusions obtained.

*Old Dominion University, Norfolk, VA, 23508

NASA Grant NSG-1135

35 *Breman, K. W. **Models for a Cryogenic Wind Tunnel With 3.2 m² Test Section; Stagnation Pressure 4-6 Bars.** National Aerospace Lab. NLR Memo-TP-76-008, June 2, 1976. 6 pp.

N81-73773

In this note some comments are given on the feasability of wind tunnel models to be used under cryogenic conditions. These comments are the result of a short and superficial investigation on this subject. The matters discussed are: materials, design and model handling. Finally the conclusion will be that no major problems are expected.

*National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

36 *Schoenmakers, T. J.: **Strain Gauge Balances for a Cryogenic Wind Tunnel With 3.2 m² Test Section and Stagnation Pressures of 4 to 6 Bars.** National Aerospace Lab. NLR-Memo-TP-76-007, June 2, 1976. 5 pp.

N81-73903

Remarks on the feasibility of using strain gauge balances in a cryogenic wind tunnel with 3.2 m² test section and stagnation pressures of 4 to 6 bars are presented in this paper. These comments are based on a short investigation and on discussions within the department of the NLR responsible for the development of strain gauge balances for the existing wind tunnels. Problems induced by the low temperatures are expected to be resolvable by executing an appropriate development program; high aerodynamic loads may put some limitations to testing relatively slender bodies.

*National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

37 *McKinney, Linwood W. and *Howell, Robert R.: **The Characteristics of the Planned National Transonic Facility.** 9th AIAA Aerodynamic Testing Conference, Arlington, Tex., June 7-9, 1976.

A76-38626 (pp. 176-184)
A76-38645#

The National Transonic Facility is a high Reynolds number transonic wind tunnel designed to satisfy the research and development needs of NASA, DOD, and industry. The facility design incorporates the cryogenic approach to achieving high Reynolds numbers with manageable model loads. By using temperature as a test variable, a unique capability to clearly separate aeroelastic, Reynolds number, and Mach number effects will be possible. This capability will open new horizons in transonic aerodynamic research. The tunnel design, including unique features and operating envelopes, is described. A brief overview of the general operating arrangement and the schedule for facility construction is presented.

*NASA, Langley Research Center, Hampton, VA, 23665

38 *Kilgore, Robert A., and *Davenport, Edwin E.: **Static Force Tests of a Sharp Leading Edge Delta-Wing Model at Ambient and Cryogenic Temperatures With a Description of the Apparatus Employed.** NASA TM-X-73901, June 1976, 50 pp.

N76-28159#

A sharp leading edge delta-wing model was tested through an angle-of-attack range at Mach numbers of 0.75, 0.80, and 0.85 at both ambient and cryogenic temperatures in the Langley 0.3-m Transonic Cryogenic Tunnel. Total pressure was varied with total temperature in order to hold test Reynolds number constant at a given Mach number. Agreement between the aerodynamic data obtained at ambient and cryogenic temperatures indicates that flows with leading-edge vortex effects are duplicated properly at cryogenic temperatures. The test results demonstrate that accurate aerodynamic data can be obtained by using conventional force-testing techniques if suitable measures are taken to minimize temperature gradients across the balance and to keep the balance at ambient (warm) temperatures during cryogenic operation of the tunnel.

*NASA, Langley Research Center, Hampton, VA, 23665

39 *Lambourne, N. C.: **Similarity Requirements for Flutter and Other Aeroelastic Models in a Cryogenic Wind Tunnel.** RAE-TM-Struct-888, June 1976. 13 pp.

N77-19083#

A consideration of the requirements for aeroelastic similarity shows that the low working temperature of a cryogenic tunnel and an ability to vary temperature both have potential advantages in regard to the choice of suitable stiffness and density scales for an aeroelastic model. The advantages are incidental to the main purpose of a cryogenic tunnel, which is to achieve high Reynolds numbers.

*Royal Aircraft Establishment, Bedford MK41 6AE, U.K.

40 *Adcock, Jerry B.; and *Ogburn, Marilyn E.: **Power Calculations for Isentropic Compressions of Cryogenic Nitrogen.** NASA TN-D-8389, Mar. 1977. 15 pp. (Formerly published as NASA TM X-73903, July 1976, N76-28516#, NASA Grant NSG-1010.

N77-20378#

A theoretical analysis has been made of the power required for isentropic compressions of cryogenic nitrogen in order to determine the extent that the drive power for cryogenic tunnels might be affected by real gas effects. The analysis covers temperatures from 80 to 310 K, pressures from 1.0 to 8.8 atm and fan pressure ratios from 1.025 to 1.200. The power required to compress cryogenic nitrogen was found to be lower than that required for an ideal diatomic gas by as much as 9.5 percent. Simple corrections to the ideal gas values were found to give accurate estimates of the real gas power values.

*NASA, Langley Research Center, Hampton, VA, 23665

41 *Hall, Robert N.: **Cryogenic Wind Tunnels: Unique Capabilities for the Aerodynamicist.** Presented at the 54th Annual Meeting of the Virginia Academy of Science, July 1976. NASA TM-X-73920. 16 pp.

N76-27252#

The cryogenic wind-tunnel concept is a practical means for improving ground simulation of transonic flight conditions. The Langley 0.3-m Transonic Cryogenic Tunnel is operational, and the design of a cryogenic National Transonic Facility is undertaken. A review of some of the unique capabilities of cryogenic wind tunnels is presented. In particular, the advantages of having independent control of tunnel Mach number, total pressure, and total temperature are highlighted. This separate control over the three tunnel parameters will open new frontiers in Mach number, Reynolds number, aeroelastic, and model-tunnel interaction studies.

*NASA, Langley Research Center, Hampton, VA, 23665

42 *Reubush, David E. **Effect of Reynolds Number on the Subsonic Boattail Drag of Several Wing-Body Configurations.** NASA TN-D-8238, July 1976 84 pp

N76-26157#

An investigation was conducted in a transonic cryogenic wind tunnel to determine the effect of varying Reynolds number on the boattail drag of several wing-body configurations. This study was made at 0° angle of attack at Mach numbers from 0.6 to 0.9 for Reynolds numbers up to 67 million (based on distance from the nose to the start of the boattail). Results indicate that as the Reynolds number was increased the boattail static pressure coefficients in the expansion region of the boattail became more negative while those in the recompression region became more positive. Results show that there was only a small effect of Reynolds number on boattail pressure drag.

*NASA, Langley Research Center, Hampton, VA, 23665

43 *Hall, Robert M.: **An Analysis of Data Related to the Minimum Temperatures for Valid Testing in Cryogenic Wind Tunnels Using Nitrogen as the Test Gas.** NASA TM-X-73924, Aug. 1976. 110 pp.

N76-29269#

The minimum operating temperature which avoids adverse low temperature effects, such as condensation, has been determined at a free stream Mach number of 0.85 for flow over a 0.137 m airfoil mounted at zero incidence in the Langley 0.3-m Transonic Cryogenic Tunnel. The onset of low temperature effects is established by comparing the pressure coefficient measured at a given orifice for a particular temperature with those measured at temperatures sufficiently above where low temperature effects might be expected to occur. The pressure distributions over the airfoil are presented in tabular form. In addition, the comparisons of the pressure coefficient as a function of total temperature are presented graphically for chord locations of 0, 25, 50, and 75 percent. Over the 1.2 to 4.5 atm total pressure range investigated, low temperature effects are not detected until total temperatures are 2 K, or more, below free-stream saturation temperatures.

*NASA, Langley Research Center, Hampton, VA, 23665

44 *Reubush, David E.: **Experimental Investigation to Validate Use of Cryogenic Temperatures to Achieve High Reynolds Numbers in Boattail Pressure Testing.** NASA TM-X-3396, Aug. 1976. 35 pp.

N76-30228#

An investigation has been conducted in the Langley 0.3-m Transonic Cryogenic Tunnel to validate the use of cryogenic temperatures to achieve high Reynolds numbers in nozzle boattail pressure testing. Tests were conducted at 0° angle of attack and at Mach numbers of 0.60, 0.85, and 0.90 on two wing-body configurations with differing boattail geometries. Test data were obtained by using two different techniques, the cryogenic method and the conventional method, to obtain the same Reynolds number. Later, the test data obtained from the two techniques on boattail pressure coefficient distributions and pressure drag coefficients were compared; results from the comparisons show excellent repeatability for all test conditions and indicate no measurable errors when using cryogenic temperatures to achieve high Reynolds numbers for nozzle boattail pressure testing.

*NASA, Langley Research Center, Hampton, VA, 23665

45 Goethert, Bernhard H.: **Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Wind Tunnel Design and Testing Techniques.** AGARD-AR-97, Aug. 1976. 23 pp.

N76-30236#

Advanced wind tunnel systems are discussed with emphasis on the impact of the cryogenic concept for high performance transonic wind tunnels. Topics covered include cryogenic operation, adjustable walls, magnetic suspensions, and laser instrumentation.

46 *Haut, Richard C., and **Adcock, Jerry B. **Prandtl-Meyer Flow Tables for Parahydrogen at Total Temperatures from 30 K to 290 K and for Nitrogen at Total Temperatures from 100 K to 300 K at Total Pressures from 1 Atm to 10 Atm.** NASA TM-X-73932, Aug 1976. 194 pp.

N76-30497#

The dependency of Mach number on the Prandtl-Meyer function was numerically determined by iterating the Prandtl-Meyer function and applying the Muller method to converge on the Mach number for flows in cryogenic parahydrogen and nitrogen at various total pressures and total temperatures. The results are compared with the ideal diatomic gas values and are presented in tabular form.

*Old Dominion University, Norfolk, VA, 23508

**NASA, Langley Research Center, Hampton, VA, 23665

47 *Howell, Robert R.; and *McKinney, Linwood W. **The U.S. 2.5-Meter Cryogenic High Reynolds Number Tunnel.** 10th ICAS Congress, Ottawa, Canada, Oct. 3-8, 1976. 12 pp.

ICAS Paper 76-04 A76-47353#

The U.S. 2.5-Meter Cryogenic High Reynolds Number Tunnel is a fan-driven transonic wind tunnel scheduled for operation in 1981. It will operate at Mach numbers from 0.1 to 1.2, stagnation pressures from 1 to 9 bars, and stagnation temperatures from 352 to 80 K. The maximum Reynolds number capability will be 120 million at a Mach number of 1.0 based on a reference length of 0.25 m. This paper describes the basis for the conceptual approach, the engineering design including unique features, and the performance operating envelopes for the tunnel.

*NASA, Langley Research Center, Hampton, VA, 23665

48 *Nicks, Oran W.: **The NTF As a National Facility.** In "High Reynolds Number Research," a workshop held at NASA, Langley, Oct. 27-28, 1976.

N77-27139 (pp. 19-51)
N77-27141#

Activities which led to the definition of the National Transonic Facility and the general agreements reached regarding its use and operations are reviewed. Topics discussed include: redefinition of test requirements, development of low cost options, consideration of a single transonic facility using existing hardware if feasible, facility concept recommendations, and acquisition schedule proposals.

*NASA, Langley Research Center, Hampton, VA, 23665

49 *Kilgore, Robert A.: **Cryogenic Wind-Tunnel Technology.** In "High Reynolds Number Research," a workshop held at NASA, Langley, Oct. 27-28, 1976.

N77-27139 (pp.53-63)
N77-27142#

The cryogenic concept and the advantages it offers with respect to achieving full scale Reynolds number in a moderate size tunnel at reasonable levels of dynamic pressure are described. Aspects which must be considered during the development of a facility that uses cryogenic gaseous nitrogen as the test gas are examined. These include the properties of nitrogen, particularly at high pressure; isentropic expansion and normal shock flows in

nitrogen; real gas ratios, and the problem of condensation. Sources of information on cryogenic technology are cited.

*NASA, Langley Research Center, Hampton, VA, 23665

50 *Gillespie, Vernon P. **The Design of Models for Cryogenic Wind Tunnels.** In "High Reynolds Number Research," a workshop held at NASA, Langley, Oct. 27-28, 1976.

N77-27139 (pp. 73-79)
N77-27144#

Factors to be considered in the design and fabrication of models for transonic cryogenic wind tunnels operating at high pressures include high model loads imposed by the high operating pressures, the mechanical and thermodynamic properties of materials in low temperature environments, and the combination of aerodynamic loads with the thermal environment. Candidate materials are being investigated to establish criteria for cryogenic wind tunnel models and their installation. Data acquired from these tests will be provided to users of the National Transonic Facility.

*NASA, Langley Research Center, Hampton, VA, 23665

51 *Guarino, Joseph F. **Instrumentation and Data Acquisition Systems.** In "High Reynolds Number Research," a workshop held at NASA, Langley, Oct. 27-28, 1976.

N77-27139 (pp. 81-101)
N77-27145#

A comprehensive and integrated measurement system was identified and a design and development effort initiated to meet the criteria imposed by the National Transonic Facility operating environment. Specific measurement areas receiving concentrated attention include: data acquisition, force measurement, pressure instrumentation, flow visualization techniques, model attitude and model deformation measurement, and temperature measurement. The NTF instrument complex will be centered around four 32-bit, 1-microsecond-cycle-time central processing units connected in a multipoint-distributed network configuration. The principle activities to be supported by these computers are: (1) data base management and processing; (2) research measurement data acquisition and display; (3) tunnel and model control, and (4) process monitoring and communication control. The distributed network approach was chosen to modularize the functional software into definable and implementable parts by the various groups involved in the design and to permit use of similar hardware configurations to improve reliability and maintainability.

*NASA, Langley Research Center, Hampton, VA, 23665

52 *Kilgore, Robert A. **The Cryogenic Wind Tunnel.** In NASA CP-2001, Advances in Engineering Science, Vol. 4, 1976, pp. 1565-1581. Presented at the 13th Annual Meeting of the Society of Engineering Science, Hampton, Va., Nov. 1-3, 1976.

N77-10368#

Based on theoretical studies and experience with a low speed cryogenic tunnel and with a 0.3-meter transonic cryogenic tunnel, the cryogenic wind tunnel concept is shown to offer many advantages with respect to the attainment of full scale Reynolds number at reasonable levels of dynamic pressure in a ground based facility. The unique modes of operation available in a pressurized cryogenic tunnel make possible for the first time the separation of Mach number, Reynolds number, and aeroelastic effects. By reducing the drive-power requirements to a level where a conventional fan drive system may be used, the cryogenic concept makes possible a tunnel with high productivity and run times sufficiently long to allow for all types of tests at reduced capital costs and, for equal amounts of testing, reduced total energy consumption in comparison with other tunnel concepts.

*NASA, Langley Research Center, Hampton, VA, 23665

53 *Baals, Donald D. **Design Considerations of the National Transonic Facility.** In NASA CP-2001, Advances in Engineering Science, Vol. 4, 1976, pp. 1583-1602. Presented at the 13th Annual Meeting of the Society of Engineering Science, Hampton, Va., Nov. 1-3, 1976.

N77-10369#

The inability of existing wind tunnels to provide aerodynamic test data at transonic speeds and flight Reynolds numbers is examined. The proposed transonic facility is a high Reynolds number transonic wind tunnel designed to meet the research and development needs of government, and the academic community. The facility employs the cryogenic approach to achieve high Reynolds numbers at acceptable model loads and tunnel power. By using temperature as a test variable, a unique capability to separate scale effects from model aeroelastic effects is provided. The performance envelope of the facility is shown to provide a ten fold increase in transonic Reynolds number capability compared to currently available facilities.

*Joint Institute for Advancement of Flight Sciences, The George Washington University, NASA, Langley Research Center, Hampton, VA, 23665

54 *Kilgore, Robert A. **Design Features and Operational Characteristics of the Langley 0.3-Meter Transonic Cryogenic Tunnel.** NASA TN D-8304, Dec. 1976. 51 pp. (This document was previously published as NASA TM-X-72012, 1974.)

N77-12071#

Experience with the Langley 0.3-m Transonic Cryogenic tunnel, which is fan driven, indicated that such a tunnel presents no unusual design difficulties and is simple to operate. Purging, cooldown, and warmup times were acceptable and were predicted with good accuracy. Cooling with liquid nitrogen was practical over a wide range of operating conditions at power levels required for transonic testing, and good temperature distributions were obtained by using a simple liquid nitrogen injection system. To take full advantage of the unique Reynolds number capabilities of the 0.3-meter transonic tunnel, it was designed to accommodate test sections other than the original, octagonal, three dimensional test section. A 20- by 60-cm two dimensional test section was recently installed and is being calibrated. A two dimensional test section with self-streamlining walls and a test section incorporating a magnetic suspension and balance system are being considered.

*NASA, Langley Research Center, Hampton, VA, 23665

55 *Stallings, R. L., Jr.; and *Lamb, M. **A Simplified Method for Calculating Temperature Time Histories in Cryogenic Wind Tunnels.** NASA TM-X-73949, Dec. 1976. 16 pp.

N77-13076#

Average temperature time history calculations of the test media and tunnel walls for cryogenic wind tunnels have been developed. Results are in general agreement with limited preliminary experimental measurements obtained in a 13.5-in. pilot cryogenic wind tunnel.

*NASA, Langley Research Center, Hampton, VA, 23665

56 *Adcock, Jerry B. **Real-gas Effects Associated With One-Dimensional Transonic Flow of Cryogenic Nitrogen.** NASA TN-D-8274, Dec. 1976. 272 pp.

N77-15345#

Real gas solutions for one-dimensional isentropic and normal-shock flows of nitrogen were obtained for a wide range of temperatures and pressures. These calculations are compared to ideal gas solutions and are presented in tables. For temperatures (300 K and below) and pressures (1 to 10 atm) that cover those anticipated for transonic cryogenic tunnels, the solutions are analyzed to obtain indications of the magnitude of inviscid flow simulation errors. For these ranges, the maximum deviation of the various isentropic and normal shock parameters from the ideal values is about 1 percent or less, which, for most wind tunnel investigations, would be insignificant.

*NASA, Langley Research Center, Hampton, VA, 23665

57 *Wagner, Bernhard, and *Schmidt, Wolfgang: **Theoretical Investigations of Real Gas Effects in Cryogenic Wind Tunnels, Final Report.** DS-FB-76/50B, Dec. 1976, 82 pp.

N79-17820#

Real gas effects in cryogenic nitrogen flows were calculated using the Beattie-Bridgeman equation of state. The investigations include Prandtl-Meyer expansions, oblique shocks, transonic small perturbation theory, transonic flow past a NACA 0012 aerofoil and shock boundary layer interaction. The two last cases mentioned were treated with the aid of finite volume techniques.

*Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

58 *Hartzuiker, J. P.: **The Proposed Cryogenic European Transonic Windtunnel (ETW).** Nederlandse Vereniging voor Luchtvaartechniek, Yearbook 1977, 1978, pp. 1.1-1.21. Based on a lecture presented to the Netherland Association of Aeronautical Engineers, Jan. 20, 1977.

A79-17118#

The proposed European Transonic Wind Tunnel is described: a cryogenic facility with test-section dimensions compatible with existing major European transonic facilities. Reynolds number based on mean aerodynamic chord lies between 25 million and 40 million. The advantages and drawbacks of cryogenic testing, as well as fundamental aspects of cryogenic aerodynamics, are discussed. Comparative estimates for capital and operating costs are presented.

*National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

59 ***National Transonic Facility Environmental Impact Statement, Final Amendment 1.** NASA TM-79372, January 1977, 188 pp.

N80-71996

I A. BACKGROUND
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*NASA, Langley Research Center, Hampton, VA, 23665

60 *Kilgore, Robert A., and *Adcock, Jerry B.: **Specific Cooling Capacity of Liquid Nitrogen.** NASA TM-X-74015, Feb. 1977, 19 pp.

N77-21261#

When cryogenic nitrogen wind tunnels are cooled by injecting liquid nitrogen directly into the tunnel, the specific cooling capacity of the nitrogen consists of the heat absorbed in warming and vaporizing the liquid plus the heat absorbed in warming the gaseous nitrogen to the tunnel stagnation temperature. The specific cooling capacity of nitrogen has been calculated for a simplified model based on this method of cooling by using a National Bureau of Standards program for the thermodynamic properties of nitrogen and the results fitted with a relatively simple equation having tunnel stagnation pressure and stagnation temperature as the independent variables. This report describes the assumed cooling process, describes the method used to calculate the specific cooling capacity of liquid nitrogen, gives the simple equation fitted to the calculated specific cooling capacity data, and presents in graphical form calculated values of the specific cooling capacity of nitrogen for stagnation temperatures from saturation to 350 K and stagnation pressures from 1 to 10 atm.

*NASA, Langley Research Center, Hampton, VA, 23665

61 *Wagner, Bernhard; and *Schmidt, Wolfgang: Theoretische Untersuchungen zur Stoss-Grenzschicht-Wechselwirkung in kryogenem Stickstoff. **(Theoretical Investigations on the Shock Wave-Boundary Layer Interaction in Cryogenic Nitrogen).** In Contributions on Transport Phenomena in Fluid Mechanics and Related Topics, Tech. Univ. Berlin, Apr. 12, 1977, pp. 277-287. Also, Zeitschrift fur Flugwissenschaften und Weltraumforschung, vol. 2, No. 2, Mar.-Apr. 1978, pp. 81-88 (In German).

N77-12402#
A77-47972#
A78-34159

(For an abstract in English, see the following entry.)

*Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

62 *Wagner, B., and *Schmidt, W.: **Theoretical Studies on the Shock Wave-Boundary Layer Interaction in Cryogenic Nitrogen.** Rept. No. ESA-TT-498, pp. 419-436, Mar. 1979. This is an English translation of the 1977 German report previously announced as N79-12402.

N79-31569#

The basic effects of low temperatures close to liquefaction in cryogenic wind tunnels were studied theoretically for viscous compressible flow on the basis of shock wave-laminar boundary layer interaction. The full Navier-Stokes equations in combination with the equations of state for a real gas and the material properties for low temperatures were solved by means of a finite volume method and MacCormack's time splitting technique. Results show relatively small deviations compared with the ideal gas case. The differences in the pressure distribution are caused mainly by real gas effects in the inviscid external flow field while the changes in the skin friction

coefficients depend mainly on the different viscosity characteristics and on the real gas effects in the temperature distribution.

*Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

63 *Haut, Richard C.: **Evaluation of Hydrogen as a Cryogenic Wind Tunnel Test Gas. Final Report.** NASA CR-145186. April 1977. 159 pp. A synopsis of this report is contained in the Journal of Aircraft, vol. 14, no. 12, Dec. 1977, pp. 1155–1156.

N77-24153#

The nondimensional ratios used to describe various flow situations in hydrogen were determined and compared with the corresponding ideal diatomic gas ratios. The results were used to examine different inviscid flow configurations. The relatively high value of the characteristic rotational temperature causes the behavior of hydrogen, under cryogenic conditions, to deviate substantially from the behavior of an ideal diatomic gas in the compressible flow regime. Therefore, if an ideal diatomic gas is to be modeled, cryogenic hydrogen is unacceptable as a wind tunnel gas in a compressible flow situation.

*Old Dominion University, Norfolk, VA, 23508

Grant NGR-47-003-052

64 *Voth, R.O.; and *Strobridge, T.R.: **Cryogenic Design and Safety Review—NASA-Langley Research Center 0.3-Meter Transonic Cryogenic Tunnel.** NASA TM-74767; NBSIR-77-857, Apr. 1977. 28 pp.

N77-28143#

A cryogenic design and safety review of a 0.3-m transonic cryogenic tunnel is presented. The tunnel working fluid and coolant is nitrogen. The nitrogen, supplied as liquid, is exhausted as a low temperature gas. The tunnel and ancillary systems are generally well designed but several recommendations to improve the cryogenic systems are made. The cost of recovering the cold vent gas is compared to the cost of producing the required liquid nitrogen using a captive air separation plant. Although the economic analysis is preliminary, it shows that because of the periodic operation of the tunnel, a captive air separation plant has a lower annual operating cost than the vent gas recovery systems considered.

*National Bureau of Standards, Boulder, CO, 80302

65 *Wagner, B.; and *Schmidt, W.: **Theoretical Investigation of Real Gas Effects in Cryogenic Windtunnels.** AIAA Paper 77-669, 10th Fluid and Plasmadynamics Conference, Albuquerque, N. Mex., June 27–28, 1977. 12 pp. Also, AIAA Journal, vol. 16, no. 6, June 1978, pp. 380–386.

A77-37023#

Real gas effects in cryogenic nitrogen flows have been calculated using the Beattie-Bridgeman equation of state. The investigations include Prandtl-Meyer expansions, oblique shocks, transonic small perturbation theory, transonic flow past a NACA 0012 aerofoil and shock-boundary layer interaction. The two last cases mentioned have been treated with the aid of finite volume techniques. The results show some noticeable deviations from the behavior of an ideal gas not only at cryogenic conditions but also at normal temperatures and high pressures. The deviations remain very small within the operating range of cryogenic wind tunnels if suitable reference quantities are used. Only the friction coefficient exhibits some systematic variation of considerable amount.

*Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

66 *Adcock, Jerry B.: **Effect of LN_2 Injection Station Location on the Drive Fan Power and LN_2 Requirements of a Cryogenic Wind Tunnel.** NASA TM-X-74036, June 1977. 19 pp.

N77-27137#

A theoretical analysis comparing the fan power and coolant (LN_2) flow rates resulting from injection of the LN_2 either upstream or downstream of the drive fan of a closed circuit transonic cryogenic tunnel is presented. The analysis is restricted to steady state tunnel operation and to the condition that the tunnel walls are adiabatic. The stagnation pressure and temperature range of the tunnel is from 1.0 to 8.8 atm and from 300 K to liquefaction temperature, respectively. Calculations are made using real gas properties of nitrogen. Results show that the fan power and LN_2 flow rates are lower if the LN_2 is injected upstream of the fan. The lower fan inlet temperature resulting from injecting upstream of the fan has a greater influence on the power than does the additional mass flow going through the fan.

*NASA, Langley Research Center, Hampton, VA, 23665

67 *Lorenz-Meyer, W.: **Ueber einige Moeglichkeiten zur Berechnung des aehnlichkeitsparameters κ^* bei Realen Gasen.** DFVLR, In "Contribution to Steady and Unsteady Aerodynamics," Aug. 1977, pp. 189-201. For translation, see NASA TM-75222, **A Few Ways of Calculating the Similarity Parameter κ^* for Real Gases.** 13 pp.

N78-17017#(In German)
N78-14121#(In English)

In connection with the question on the applicability of test results obtained from cryogenic wind tunnels to the large-scale model the similarity parameter is referred to. A simple method is given for calculating the similarity parameter. From the numerical values obtained it can be deduced that nitrogen behaves practically like an ideal gas when it is close to the saturation point and in a pressure range up to 4 bar. The influence of this parameter on the pressure distribution of a supercritical profile confirms this finding.

*DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

68 *Buongiorno, C.: La Galleria Transonica Internittente Criogenica per Gli Altissimi Numeri di Reynolds. **(Cryogenic Intermittent Transonic Wind Tunnel for Very High Reynolds Numbers).** Paper presented at the 4th National Congress of the Italian Association of Aeronautics, Milan, Italy, Sept. 19–23, 1977. 21 pp. (In Italian).

A78-49739

The current status of U.S. and European studies on a very-high-Reynolds-number transonic wind tunnel is reviewed and a tunnel to be used by the Italian Aerospace Industries is proposed in the form of a transonic wind tunnel that makes use of both blow-down and cryogenic technology. The proposed wind tunnel measures 1×1.2 m and has the following characteristics: Reynolds number—30 million; Mach number—0.8-1.2; total temperature—120 K; total pressure—520 KPa. Use of a sleeve valve significantly reduces turbulence intensity in the test section compared to the values normally obtained in a continuous wind tunnel. The air temperature is reduced to the desired stagnation temperature in an economical way through use of a regeneration heat exchanger. The relative low cost of the facility is given and its complementary use with the proposed European cooperative transonic wind tunnel is discussed.

*Roma Universita, Rome, Italy

69 *Christophe, Jean: Genese du Projet de Soufflerie Transsonique Europeenne a Grand Nombre de Reynolds. **(Genesis of the European High-Reynolds-Number Transonic Wind Tunnel Project.)** Association Aeronautique et Astronautique de France, 14th

Colloque d'Aerodynamique Appliquee, Toulouse, France, Nov. 7-9, 1977. Also L'Aeronautique et l'Astronautique, no. 72, 1978, pp. 21-34. (In French.)

A79-17769

The proposed cryogenic wind tunnel project, which would involve cooperation by West Germany, France, The Netherlands, and the United Kingdom, is described. Reasons for performing high-Reynolds-number experiments are discussed, and examples of proposed problems and their analysis are examined. Reasons for selecting the cryogenic design are considered with attention to the history of the wind tunnel project and the performance of pilot-study wind tunnels.

*ONERA, BP 72, 92322 Chatillon Cedex, France

70 *Faulmann, D.; *Prieur, J.; and *Vergnolle, J. F.: Essais Preliminaires sur une Installation Transsonique Fonctionnant par Rafales Cryogeniques. **(Preliminary Tests of a Transonic Installation Functioning With Cryogenic Gusts.)** Association Aeronautique et Astronautique de France, AAAF-NT-78-26, 15 pp. Presented at the 14th Colloque d'Aerodynamique Appliquee, Toulouse, France, Nov. 7-9, 1977. Available NTIS and CEDOCAR, Paris. (In French.).

N79-23040#

To achieve in-flight Reynolds numbers, a preliminary system operative at low temperatures for a short period in a transonic wind tunnel is discussed and evaluated. Injection of liquid nitrogen at a point in the fluid circuit rapidly induces low temperatures for a test period on the order of 10 sec. This technique of increasing the Reynolds number without introducing severe instrumentation problems (as is the case with continuous cryogenic systems) permits adaptation of existing transonic wind tunnels to an extended Reynolds number range. An induction system with primary air cooled to 80 K was also tried with negative results since it was not possible to reduce the main circulation temperature below 200 K.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

71 *Christophe, J.: Projet de Soufflerie Transsonique Europeenne A Grand Nombre de Reynolds. **(Transonic European Wind Tunnel Project for High Reynolds Numbers.)** Association Aeronautique et Astronautique de France, AAAF-NT-78-01. Presented at the 14th Colloque d'Aerodynamique Appliquee, Toulouse, France, Nov. 7-9, 1977. 34 pp. Available NTIS and CEDOCAR, Paris. (In French.)

N79-23118#

Work from 1968 to the final joint recommendation to build a cryogenic transonic high Reynolds number wind tunnel for European governments is discussed. Such a project is necessary since actual flight performance differs from low Reynolds number transonic wind tunnel results. Several alternatives were proposed and experimentally tried in pilot tests. The cryogenic solution was finally recommended as static pressure and power can be kept low for the same Reynolds number. The proposed wind tunnel is 1.95×1.65 m square, with maximum pressure at 4.4 bars, minimum temperature at 120 K, Mach number up to 1.35, and Reynolds number up to 40 million when working with nitrogen instead of air.

*ONERA, BP 72, 92322 Chatillon Cedex, France

72 *Dupriez, F.: Similitude, Realisation, Identification et Instrumentation des Maquettes d;Essais. **(Similitude, Manufacturing, Identification, and Instrumentation of Test Models.)** Association Aeronautique et Astronautique de France, AAAF-NT-78-24. 38 pp. Presented at the 14th Colloque d'Aerodynamique Appliquee, Toulouse, France, Nov. 7-9, 1977. Available NTIS and CEDOCAR, Paris. (In French.).

N79-23120#

Several aspects of present aircraft model technology are surveyed. Similitude and practical choice rules are discussed as well as identification and instrumentation techniques. Specifications and manufacturing are illustrated with several practical examples, such as use of high technology composite materials (carbon and boron fibers); increasing application of numerical control manufacturing techniques, the rapid development of microprocessor use, and adaptation to basic technological changes such as cryogenic wind tunnels.

*University of Science & Technology, Lille, France

73 *Bazin, M.: Problemes de Construction de Maquettes pour les Souffleries a Grand Nombre de Reynolds. **(Construction Problems Specific to Models for High Reynolds Number Wind Tunnels.)** Association Aeronautique et Astronautique de France, AAAF-NT-78-02. ONERA-NT-1978-6 45 pp. Presented at the 14th Colloque d'Aerodynamique Appliquee, Toulouse, France, Nov. 7-9, 1977. Available NTIS and CEDOCAR, Paris. (In French.) (The English translation follows as the next entry.)

N79-23124#

The state of the art is surveyed for both pressurized and cryogenic wind tunnel alternatives. Materials, feasible dimensions, safety problems, cost, instrumentation, etc., are discussed by model construction experts. Feasibility is demonstrated, although an effort to reduce developing time is still necessary. Present limitations include balances and model supports. New methods or materials will be necessary to replace local gages in the case of cryogenic systems.

*ONERA, BP 72, 92322 Chatillon Cedex, France

74 *Bazin, Maurice: **Construction Problems for High Reynolds Number Wind Tunnel Models.** Presented at the 14th Colloque d'Aerodyn. Appl. de l'Assoc. Aeron. et Astron. de France, Toulouse, France, Nov. 7-9, 1977. European Space Agency, Paris, France Rep. No. ESA-TT-564, June 1979. 50 pp. This is the English translation of ONERA-NT-1978-6.

N80-12101#

Design structures, problems of definition, and materials for high Reynolds number wind tunnel models are discussed. Models for force and pressure distributions, air intakes, jet simulation, and dynamic flutter are considered. It is shown that deformations in operation under the effect of aerodynamic and thermal loads require new measuring techniques and the adaptation of the capacity, thermal protection, and calibration methods of the balance. The mechanical strength of the supports, in particular the risk of divergence, and the dynamic behavior of the mountings are the most severe limitations in the use of pressurized wind tunnels. Thermal problems are added in a cryogenic environment. The development of pressure measurement methods and instruments is considered.

*ONERA, BP 72, 92322 Chatillon Cedex, France

75 *Stollery, J. L.; and **Murthy, A. V.: **An Intermittent High-Reynolds-Number Wind Tunnel.** Aeronautical Quarterly, vol. 28, Nov. 1977, pp. 259-264. (A78-20193). AIAA 10th Aerodynamic Testing Conference, San Diego, Calif., Apr. 19-21, 1978. Also, 11th ICAS Congress, Lisbon, Portugal, Sept. 10-16, 1978, Proceedings, vol. 1, pp. 461-465. (A79-20116#).

AIAA paper 78-766 A78-32327#

The paper suggests a simple method of generating intermittent reservoir conditions for an intermittent, cryogenic wind tunnel. This can be done by operating some existing types of short-duration tunnels "in reverse." Two examples are considered: (1) a modification of the Ludwieg Tube and (2) the Isentropic Light Piston Tunnel.

The sizes of tunnels required to meet the European and American specifications for a high Reynolds number tunnel with a 10 second running time are given together with proposals for a more modest national or university facility with a one second test time.

*Cranfield Institute of Technology, Cranfield, Bedford MK43 OAL, U.K.

**National Aero. Lab., Bangalore, India

76 *Haut, Richard Carl: **Evaluation of Hydrogen as a Cryogenic Wind Tunnel Test Gas.** Ph.D. Thesis, Old Dominion Univ., 1977. 160 pp. Available Univ. Microfilms, Order #77-17259.

N78-12103

A theoretical analysis of the properties of hydrogen was made to determine the suitability of hydrogen as a cryogenic wind tunnel test gas. By using cryogenic hydrogen a significant increase in the test Reynolds number is achieved without increasing the aerodynamic loads. Nondimensional ratios used to describe various flow situations in hydrogen determined that cryogenic hydrogen is unacceptable as a wind tunnel test gas in a compressible flow situation. At low Mach numbers, however, in the incompressible flow regime, cryogenic hydrogen is acceptable. Hydrogen properties and fan drive-power requirements related to a hydrogen wind tunnel were also examined.

*Old Dominion University, Norfolk, VA, 23508

77 *Goodyer, M. J.: **The 0.1 m Subsonic Cryogenic Tunnel at the University of Southampton.** NASA CR-145305, Jan. 1978. 43 pp.

N78-18086#

The design and performance of a low speed one atmosphere cryogenic wind tunnel is described. The tunnel is fan driven and operates over the temperature range 305 K to 77 K at Mach numbers up to 0.28. It is cooled by the injection and evaporation of liquid nitrogen in the circuit, and the usual test gas is nitrogen. The tunnel has a square test section 0.1 m across and was built to allow, at low costs, the development of testing techniques and the development of instrumentation for use in cryogenic tunnels, and to exploit in general instrumentation work the unusually wide range of unit Reynolds number available in such tunnels. The tunnel was first used in the development of surface flow visualization techniques for use at cryogenic temperatures.

*The University, Southampton SO9 5NH, Hampshire, U.K.

NASA Grant NSG-7172

78 *Ray, Edward J.: **Langley's Two-Dimensional Research Facilities: Capabilities and Plans.** In "Advanced Technology Airfoil Research," Vol. 1, Part I, Mar. 7-9, 1978.

N79-20030 (pp. 399-414)
N79-20055#

The current capabilities and the forthcoming plans for Langley's two-dimensional research facilities are described. The characteristics of the Langley facilities are discussed in terms of Reynolds number, Mach number, and angle-of-attack capabilities. Comments are made with regard to the approaches which have been investigated to alleviate typical problem areas such as wall boundary effects. Because of the need for increased Reynolds number capability at high subsonic speeds, a considerable portion of the paper deals with a description of the 20 by 60 cm two-dimensional test section of the Langley 0.3-m Transonic Cryogenic Tunnel, which is currently in the calibration and shakedown phase.

*NASA, Langley Research Center, Hampton, VA, 23665

79 *Ladson, Charles L.: **A New Airfoil Research Capability.** In "Advanced Technology Airfoil Research," Vol. 1, Part I, Mar. 7-9, 1978.

N79-20030 (pp. 425-432)
N79-20057#

The design and construction of a self-streamlining wall test section for the Langley 0.3-m Transonic Cryogenic Tunnel was included in the fiscal year 1978 construction of facilities budget for Langley Research Center. The design is based on the research being carried out by M. J. Goodyer at the University of Southampton, Southampton, England, and is supported by Langley Research Center. This paper presents a brief description of the project. Included are some of the design considerations, anticipated operational envelope, and sketches showing the detail design concepts. Some details of the proposed operational mode, safety aspects, and preliminary schedule are presented.

*NASA, Langley Research Center, Hampton, VA, 23665

80 *Nicks, Oran W.; and *McKinney, Linwood W.: **Status and Operational Characteristics of the National Transonic Facility.** 10th AIAA Aerodynamic Testing Conference, San Diego, Calif., Apr. 19-21, 1978. Technical Papers, pp. 40-42.

AIAA paper 78-770 A78-32331#

This paper discusses the development and capabilities of the National Transonic Facility which is planned for operation in 1981. The fan-drive, cryogenic-pressurized, closed-return facility will have operating parameters of: 0.1-1.2 Mach, 1-9 bars pressure, 78-340 K, 150 dB sound pressure, and ±0.001 rms turbulence intensity. These operating conditions have been selected on the basis of several current and future aircraft and space transportation systems. The facility will provide full-scale testing conditions for calculating subsonic drag, airloads, and stability and control information. Data for pre-test conditions, on-line information, and post-test analysis will be computer-processed.

*NASA, Langley Research Center, Hampton, VA, 23665

81 *Inger, G. R.: **On the Simulation of Transonic Shock-Turbulent Boundary Layer Interactions in Cryogenic or Heavy Gas Wind Tunnels.** VPI-Aero-080, April 1978. 26 pp. Presented at 10th AIAA Aerodynamic Testing Conference, San Diego, Calif., pp. 285-292. Apr. 19-21, 1978. Also Journal of Aircraft, vol. 16, no. 4, April 1979, pp. 284-287.

AIAA paper 78-808 N78-24501#
A78-32362#

The role of the basic similitude parameters governing transonic normal shock-turbulent boundary layer interaction effects in cryogenic wind tunnel tests is studied theoretically for the non-separating case. Besides Mach and Reynolds number, these parameters are the wall to total temperatures ratio, specific heat ratio γ, viscosity-temperature exponent and Prandtl number. The results show that lack of temperature ratio simulation has a significantly adverse effect on interactive skin friction and hence separation onset compared to the adiabatic free flight case; higher γ's than air also may have some effect.

*Virginia Polytechnic Institute and State University, Blacksburg, VA, 24060

82 *Hall, Robert M.: **Condensation and Its Growth Down the Test-Section of the Langley 0.3-M Transonic Cryogenic Tunnel.** 10th AIAA Aerodynamic Testing Conference, San Diego, Calif., Apr. 19-21, 1978, Technical Papers, pp. 301-304.

AIAA paper 78-811 A7[illegible]-32365#

Four total pressure probes were used to measure the growth of condensation down the test section of the Langley 0.3-m tunnel, and the condensation data were employed to verify a mathematical model which assumes condensation results from heterogeneous nucleation on preexisting seed particles. The onset of effects occurs throughout the test section at the same total temperature but the magnitude of the effects increases with increasing length down the test section. Condensation is important because it determines the minimum operating temperature of transonic cryogenic wind tunnels.

*NASA, Langley Research Center, Hampton, VA, 23665

83 *Hartzuiker, J. P.; and *North, R. J.: **The European Transonic Wind-Tunnel Project.** ICEC 7; Proceedings of the 7th Int. Cryogenic Engineering Conference, London, England, July 4-7, 1978, pp. 322-330.

A79-31021

In 1978, four European nations agreed to cooperate in developing a large transonic high-Reynolds-number wind tunnel which would use cold nitrogen gas as the test medium. A test section size of 1.95 m×1.65 m is envisaged. A continuous fan drive would provide runs with 10 periods of data acquisition, each lasting 10 sec; a typical day could yield four runs. Cryogenic engineering problems related to the construction of the wind tunnel are also considered.

*Technical Group, ETW, National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

84 *Michel, R.; and *Faulmann, D.: **Preliminary Tests in a Cryogenic Transonic Wind Tunnel Driven by Induction.** ONERA TP-1978-48E. Also, La Recherche Aerospatiale, vol. 185, no. 4, July-Aug. 1978, pp. 205-207. (In French).(For an abstract in English, see the following entry.)

A79-15300#

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

85 *Michel, R.; and *Faulmann, D.: **Preliminary Tests in a Cryogenic Wind Tunnel Driven by Induction.** ONERA-TP-1978-48E, July 1978. 9 pp. Translated into English from La Recherche Aerospatiale, Bulletin Bimestriel (Paris) No. 1978-4, July-Aug. 1978, pp. 205-207.

N80-12019#

A ¼ scale cryogenic operation pilot wind tunnel test for higher Reynolds number was performed to verify a liquid nitrogen injection fast cooling process. The cryogenic operation was combined with an induction driven operation in the hope that the short flow duration will give rise to a decrease in the wall and model surface temperature only, avoiding some technological problems. Operation temperatures down to 100 K were obtained. Thin layers of wall insulation are shown to be efficient in containing nitrogen consumption. It is concluded that the simplicity of implementation makes the process promising for adapting existing wind tunnels to cryogenic operation.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

86 *Hottner, T.: Anwendung der Tieftemperaturtechnik im stromungstechen Versuchswesen. **(The Application of Cryogenics in Experimental Aerodynamics).** Ingenieur-Archiv, vol. 47, no. 4, 1978, pp. 241-256. For translation, see NASA TM-75385.

A78-48982 (In German)
X79-10099 (Translation)

The application of cryogenics in wind tunnel design offers an increase in Reynolds number simulation at simultaneously reduced drive power for the wind tunnel compressor compared to a wind tunnel driven at normal temperatures. The price, however, is an additional cryogenic power. The report is concerned with the energetic aspect of cryotechnics in wind tunnel technique. With restriction only on cryogenic power due to tunnel process-heat, the continuously running tunnel with closed circuit and the blow-down-storage tunnel are investigated. Finally, the possibility of reducing cryogenic power using heavy gases as test medium is discussed.

*Stuttgart University, Pfaffenwaldring 21, D-7000 Stuttgart 80, West Germany (FRG)

87 *Hartzuiker, J. P.; and *North, R. J.: **The European Transonic Windtunnel (ETW) for High Reynolds-Number Testing.** Presented at the 11th Congress of ICAS, Lisbon, Spain, 11-16 Sept. 1978, Rep. No. TG-ETW/D2, Sept. 1978. 9 pp.

A81-14387# (pp. 94-103)

A joint project of four nations (France, Germany, The Netherlands, and U. K.) to define, and later to construct, a new European high-Reynolds-number transonic windtunnel using cold nitrogen gas as the test medium is described. The concept of windtunnel testing at cryogenic temperatures is discussed and a brief description of the proposed tunnel, as it is envisaged at present, is given.

*Technical Group, ETW, National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

88 *Kell, D. M.: **A Surface Flow Visualization Technique for Use in Cryogenic Wind Tunnels.** Aeronautical Journal, vol. 82, Nov. 1978, pp. 484-487.

A79-20795

A method of surface flow visualization for use in cryogenic wind tunnels is described which requires injection of a cryogenic liquid onto the model while the tunnel is running. This necessitates the use of a substance that remains liquid over a large range of cryogenic wind tunnel operating temperatures. It is found that propane (C_3H_8) is a suitable substance. Experiments are conducted in a subsonic cryogenic wind tunnel to assess the practical application of liquid propane flow visualization. The propane is stored in a chamber cooled by liquid nitrogen and when required is pumped through pipes to a gallery inside the model and then out onto the surface through small holes. To color the liquid a suspension of pigment particles is used. Propane is supplied to the cooled chamber in gaseous form from a standard liquefied gas cylinder. The sequence of events is illustrated on a propane temperature-entropy diagram. The use of liquefied propane for flow visualization in a cryogenic wind tunnel operating at pressures up to 40 atm appears to be feasible. Illustrative examples are provided.

*British Aerospace, Weybridge, Surrey, U.K.
Grant NSG-7172

89 *Clausing, A. M.; *Clark, G. L.; and *Mueller, M. H.: **The Cryogenic Heat Transfer Tunnel—A New Tool for Convective Research.** Presented at the Winter Annual Meeting, ASME, San Francisco, Calif., Dec. 10-15, 1978, pp. 73-78.

A79-24316#

A novel heat transfer technique, the use of cryogenic temperatures for convective modeling, is used in this study in order to simultaneously obtain large Grashof and Reynolds numbers on a vertical cylinder. The research is motivated by the need to predict combined convective losses from large, high-temperature objects such as solar "power tower" receivers where the magnitudes of both the Grashof and Reynolds numbers are large. The cryogenic heat transfer tunnel provides an economical method of obtaining these large Grashof and Reynolds numbers with an appropriate and

nearly constant Prandtl number, thus it is an excellent tool for study of convective heat transfer. Low-temperature modeling, a cryogenic testing facility, and a transient measurement technique are discussed.

*University of Illinois at Urbana-Champaign, Urbana, IL, 61801
Research supported by Dept. of Energy
Research Grant No. 87-9180

90 *Hall, Robert M., and **Kramer, Susan A. **A Review of "At Rest" Droplet Growth Equations for Condensing Nitrogen in Transonic Cryogenic Wind Tunnels.** NASA TM-78821, Jan 1979. 36 pp.

N79-15001#

Droplet growth equations are reviewed in the free-molecular, transition, and continuum flow regimes with the assumption that the droplets are "at rest" with respect to the vapor. As comparison calculations show, it is important to use a growth equation designed for the flow regime of interest. Otherwise, a serious over-prediction of droplet growth may result. The growth equation by Gyarmathy appears to be applicable throughout the flow regimes and involves no iteration. His expression also avoids the uncertainty associated with selecting a mass accommodation coefficient and, consequently, involves less uncertainty in specifying adjustable parameters than many of the other growth equations.

*NASA, Langley Research Center, Hampton, VA, 23665
**University of Virginia, Charlottesville, VA, 22901

91 *Bursik, Joseph W.; and **Hall, Robert M.: **Metastable Sound Speed in Gas-Liquid Mixtures.** NASA TM-78810. Mar. 1979. 54 pp.

N79-20339#

A new method of calculating speed of sound for two-phase flow is presented. The new equation assumes no phase change during the propagation of an acoustic disturbance and assumes that only the total entropy of the mixture remains constant during the process. The new equation predicts single-phase values for the speed of sound in the limit of all gas or all liquid and agrees with available two-phase, air-water sound speed data. Other expressions used in the two-phase flow literature for calculating two-phase, metastable sound speed are reviewed and discussed. Comparisons are made between the new expression and several of the previous expressions—most notably a triply isentropic equation as used, among others, by Karplus and by Wallis. Appropriate differences are pointed out and a thermodynamic criterion is derived which must be satisfied in order for the triply isentropic expression to be thermodynamically consistent. This criterion is not satisfied for the cases examined, which included two-phase nitrogen, air-water, two-phase parahydrogen, and steam-water. Consequently, the new equation derived is found to be superior to the other equations reviewed.

*Rensselaer Polytechnic Institute, Troy, NY, 12181
**NASA, Langley Research Center, Hampton, VA, 23665

92 **First International Symposium on Cryogenic Wind Tunnels.** University of Southampton, U. K., April 3-5, 1979.

A80-24077

The first paper presented served as an introduction to the conference. The history of the development of cryogenic wind tunnels was given and suggestions made for future research to make tunnels of this kind even more valuable. Thirty-five additional papers were presented grouped under the following topics: Instrumentation, Cryogenic Tunnels with Magnetic Levitation, Liquid and Gaseous Nitrogen Flow Properties, Cryogenic Tunnel Technology, Tunnel Controls, Heat Transfer Topics, Model Design, and Reports on Tunnel Projects. (Copies of this Symposium are available from Dr. M. J. Goodyer, Dept. of Aeronautics & Astronautics, The University, Southampton SO9 5NH, Hampshire, U.K.)

93 *Goodyer, M. J. **The Evolution of the Cryogenic Wind Tunnel.** Paper no. 1, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24078#

The main aim of this paper is to trace the key events in the emergence of the cryogenic wind tunnel, events which led therefore to this Symposium, to learn of its present state of development and to gain insight into the future pattern of evolution. A secondary aim is to attempt to influence evolution by drawing attention to areas of endeavour which are not receiving the degree of research effort which may be justified.

*The University, Southampton SO9 5NH, Hampshire, U.K.

94 *Bazin, Maurice; and *Dubois, Maurice: **Balance and Sting Design for Cryogenic Wind Tunnels.** Paper no. 2, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979. ONERA-TP-1979-40.

A79-39089#

The orientations and thoughts leading to the concept of balances and stings usable in the future European Transonic Windtunnel (ETW) are presented in this paper. They constitute the starting point of a national research program, integrated within the European program. The domain considered is that of ETW cryogenic runs of about 10 minutes, from 120 to 300 K; stagnation pressure 1 to 4.4 bar; Mach 0.2 to 1.35.

*ONERA, BP 72, 92322 Chatillon Cedex, France

95 *Krogmann, Paul; and *Lorenz-Meyer, Wolfgang: **Design and Testing of an Unheated Strain Gauge Balance Element for Cryogenic Temperatures.** Paper no. 3, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24079#

In order to develop unheated strain gauge balances for use in cryogenic wind tunnels at low temperatures, experiments were undertaken at DFVLR Goettingen on single-component elements which were made of different steels and were equipped with different types of strain gauges. Disappointingly bad results were obtained when unsuitable strain gauges were used on two identical elements of austenitic stainless steel. Subsequent experiments with another type of strain gauge on the same elements showed better but still poor results, which obviously have to be attributed to temperature dependent variations of the material properties. Finally, another element was manufactured of different steel. This element in connection with suitable strain gauges, so far has given most promising results.

*DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

96 *Liousse, F.; *Calvet, P., and *Giovannini, A. **Experimental Study of Thermoresistive Sensors Under Cryogenic Conditions.** Paper no. 4, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24080#

Thermoresistive sensors (commercially available "hot" wire or film type probes) are tested under steady and unsteady cryogenic flows in order to determine their aptitude to operate in cryogenic wind tunnels for instantaneous temperature and velocity measurements. Some specific devices have been designed. They consist of a small calibration tunnel performing controlled velocity variations and an electronic thermometer with a built-in circuit which permits

in situ measurement of response time of the sensors.

*ONERA/CERT, BP 4025, 31055 Toulouse, Cedex, France

97 *Hartzuiker, J. P., and *North, R. J.: **A Progress Report on the European Transonic Windtunnel Project.** Paper no. 5, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24082#

This paper was written about a year after the start of the Preliminary Design Phase of ETW. The organizational structure was established, the preliminary design of the pilot tunnel was finished and that of ETW was well under way. A substantial cryogenic technology programme had been initiated. Strong support was being given from many quarters to the work of the Technical Group. A further Memorandum of Understanding for the next Phase or Phases was under consideration and preparations were being made for a decision on the site. This all represented real progress towards the realization of the European Transonic Windtunnel in the mid-1980's.

*Technical Group, ETW, National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

98 *Nelander, Curt: **A Self-Contained Cryogenic Air Supply System for a Transonic Blow-Down Tunnel.** Paper no. 6, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K. Apr. 3-5, 1979.

A80-24083#

A high pressure air supply system can be used not only to feed a wind tunnel but also to reduce the total enthalpy of the gas. This can be done by various methods and to such an extent that cryogenic stagnation temperatures are achieved. The paper deals with some different methods which could be used to incorporate the cold-generating process into the wind tunnel run sequence. It is shown that with a huge low pressure air storage already on hand (as the case is at FFA) the most attractive scheme should be to store the cold outlet air from the tunnel and to use this low enthalpy gas for cooling off the compressed air when the high pressure storage is recharged.

*Aktiebolaget Rollab, Jarvstigen 5, Box 7073, S-171 07 Solna, Sweden

99 *Ashcroft, D. H.; and *Emslie, K.: **A Cryogenic Transonic Blowdown Wind Tunnel Project.** Paper no. 7, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24084#

Combat aircraft operate within the range of serious scale effects and hence wind tunnel tests require full simulation of Reynolds number if seriously misleading results are to be avoided. Although there are many claims on the capital within the aircraft industry the provision of a high Reynolds number facility will produce cost effective returns. Means to achieve this are considered relative to capital and running costs. Long experience with a blowdown to atmosphere wind tunnel has been taken as the basis for a cryogenic version. Injection and evaporation of liquid nitrogen downstream of the airflow control valve will cool the test gas to flow across a previously cooled model. The test gas will be discarded, despite the high cost per run, because the alternatives which employ natural cooling processes, recirculation or energy saving would be much more costly to build. The major features of the project and potential performance are described. Comments are made on the key areas requiring experimental development work and on the program that will be undertaken to produce a successful facility.

*British Aerospace, Wharton Aerodrome, Preston PR4 1AX, Lancashire, U.K.

100 *Hutt, G. R., and *East, R. A.: **Preliminary Studies of a Free Piston Expander for an Intermittent Cryogenic Wind Tunnel.** Paper no. 8, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24085#

The purpose of the current work is to present preliminary experimental results of measurements of the tunnel stagnation temperatures which may be achieved in a small scale free piston device and to determine the effect of heat transfer from the tube on the uniformity of the conditions achieved. Results are presented of experiments using a small scale free piston expansion drive system proposed by Stollery and Murthy for an intermittent cryogenic wind tunnel. The feasibility of the proposed operating principle has been demonstrated and measurements of pressure and temperature during the expansion and run periods are compared with the predictions of a simple theoretical model.

*The University, Southampton SO9 5NH, Hampshire, U.K.

101 *Haldeman, Charles W.; **Kramer, Richard, A.; and *Way, Peter: **Developments at M.I.T. Related to Magnetic Model Suspension and Balance Systems for Large Scale Facilities.** Paper no. 9, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24087#

Magnetic model suspension and balance systems for wind tunnel use have been designed, tested and used at M.I.T.'s Aerophysics Laboratory for over eighteen years. Despite this experience, which demonstrates the utility and durability of the magnetic model suspension and balance systems, no large-scale system has yet been constructed for use anywhere in the world. This appears to be principally due to the large capital cost of such a facility. This paper presents several attributes of magnetic balance systems which make them attractive for use in large-scale cryogenic facilities and reports on recent developments in model roll control and superconducting coil construction, which enhance system versatility and reduce the electrical power requirements.

*Aerophysics Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 02139

**Arizona State University, Tempe, AZ, 85281

102 *Britcher, C. P.; *Goodyer, M. J.: **The Southampton University Magnetic Suspension/Cryogenic Wind Tunnel Facility.** Paper no. 10, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24088#

Scaling laws relating design parameters of magnetic suspension and balance systems to wind tunnel test conditions are identified. Reduction of test temperature is found to be the most attractive and powerful technique of reducing the cost of a magnetic suspension facility for specific test Reynolds number and Mach number requirements. Details of the adaption of a small, low-speed, fan driven cryogenic wind tunnel for use with a magnetic suspension and balance system are given. Aerodynamic data have been acquired from a model suspended in the new facility over a wide range of tunnel conditions. Temperature is shown to have small effect on the magnetization of the model magnetic cores. Studies of the effect have begun.

*The University, Southampton SO9 5NH, Hampshire, U.K.

103 *Kilgore, R. A.; *Igoe, William B.; *Adcock, Jerry B.; *Hall, Robert M.; and *Johnson, Charles B.: **Full-Scale Aircraft Simulation With Cryogenic Tunnels and Status of the National Transonic Facility.** Paper no. 11, 1st Int. Symp. on Cryogenic Wind Tunnels,

Southampton, U.K., Apr. 3-5, 1979. NASA TM-80085 18 pp. (N79-26064#).

A80-24090#

Theoretical studies to determine the effect of thermal and caloric imperfections in cryogenic nitrogen on boundary layers indicate that in order to simulate nonadiabatic laminar or turbulent boundary layers in a cryogenic nitrogen wind tunnel, the flight enthalpy ratio, rather than the temperature ratio, should be reproduced. The absence of significant real-gas effects on both viscous and inviscid flows makes it unlikely that there will be large real-gas effects on the cryogenic tunnel simulation of shock boundary-layer interactions or other complex flow conditions encountered in flight. Experimental and theoretical studies on condensation effects to determine the minimum usable temperature indicate that under most circumstances free-stream Mach number rather than maximum local Mach number determines the onset of condensation effects. Progress is well underway on a major application of the cryogenic wind-tunnel concept with the construction of the U.S. National Transonic Facility at the Langley Research Center. This new tunnel is scheduled to become operational by 1982. Not only will it provide an order of magnitude increase in Reynolds number capability over existing U.S. tunnels, but also because of the ability to vary pressure, Mach number, and temperature independently, it will be able to perform the highly desirable research task of separating aeroelastic, compressibility, and viscous effects on the aerodynamic parameters being measured.

*NASA, Langley Research Center, Hampton, VA, 23665

104 *Edmundson, I. C.: **The Generation of Cryogenic Temperatures by High Pressure Expansion.** Paper no. 12, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979

A80-24091#

In designing an intermittent cryogenic tunnel it would seem logical to create the conditions intermittently. Stollery proposed that this could be done by using the expansion of a high pressure gas. A proposed scheme is explained. In the calculation an adiabatic, isentropic expansion was assumed. This paper reviews the available experimental evidence to examine this assumption. From the evidence presented, the deviations from an adiabatic, isentropic expansion has important implications for the design of this tunnel. Previous experimental work on the expansion of gases has shown that these deviations are significant. Experimental work is being carried out to assess a more realistic configuration.

*Cranfield Institute of Technology, Cranfield, Bedford MK43 0AL, U.K.

105 *Blanchard, A., and *Faulmann, D. **Progress Report on a Cryogenic Pilot Transonic Wind Tunnel Driven by Induction.** Paper no. 13, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24092#

A promising solution to increase the Reynolds number without producing too many technological problems seems to be provided by a short cryogenic operating run, in which the cooling is ensured by a quick injection of liquid nitrogen in the return leg circuit. A thin layer of internal thermal insulation allows a reduction of thermal losses and nitrogen consumption. This solution has been chosen for transforming existing wind tunnels, and in particular for the adaptation of T2 for cryogenic operation. In our present installation we are studying and resolving satisfactorily many problems connected with general cryogenic wind tunnel functioning. Many problems of low temperature operation must be solved through such fundamental studies before the error free realization of larger tunnels can be made.

*ONERA/CERT, BP 4025 31055 Toulouse Cedex, France

106 *Luneau, James; *Rochas, Noel; and *Kirrmann, Clement **Preliminary Study of the Injection Process of LN_2 in a Cryogenic Wind-Tunnel.** Paper no. 14, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24093#

The Ecole Nationale Superieure de l'Aeronautique et de l'Espace (ENSAE) in collaboration with the Centre d' Essais Aeronautique de Toulouse (CEAT) has been studying a transonic cryogenic wind-tunnel. This wind-tunnel, which is now being built, is to be operational by the end of 1980. It has been conceived to study airfoils in the transonic field. To be sure that the liquid nitrogen has disappeared inside the test section, a study was made to determine the characteristics and the location of injectors able to maintain a monophasic, steady uniform flow in the test section. The theoretical study is being oriented towards modelling of breakup and coalescence phenomena. A small wind tunnel with a 60 mm×120 mm test-section is now being built and will be used to study the influence of different parameters, such as injection velocity, gas flow velocity, and gas temperature. The final aim consists in validating a theoretical model of the diphasic flow, which should allow us to determine the optimal characterics and position of the LN_2 injectors to be set in the ENSAE wind tunnel and other cryogenic wind tunnels of the future.

*ENSAE/CEAT, BP 4032, 31055 Toulouse Cedex, France

107 *Koppenwallner, G., and *Dankert, C. **The Homogeneous Nitrogen Condensation in Expansion Flows With ETW-Relevant Stagnation Conditions.** Paper no. 15, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979

A80-24095#

The condensation in free jet expansions with stagnation conditions typical for transonic cryo-tunnels was studied. The results show the delay for condensation onset and the gas dynamic behavior within the condensation regime. Although the experiments were performed in small scale nozzles, they nevertheless can be used to predict condensation delay in model flow fields.

*DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

108 *Younglove, B. A. **Thermodynamic Properties of Nitrogen Gas From Sound Velocity Measurements.** Paper no. 16, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979

A80-24096#

Thermodynamic properties of nitrogen gas have been calculated from 80 K to 350 K and at pressures to 10 bar from sound speed measurements and existing P-V-T data using multiproperty fitting techniques. These new data are intended to improve existing predictive capability of the equation of state in the low density region needed for use with the National Transonic Facility (NTF) now being built at the NASA Langley Research Center.

*National Bureau of Standards, Boulder, CO 80302

109 *Albone, C. M. **An Investigation Into the Real Gas Effects of Cryogenic Nitrogen in Inviscid Homentropic Flow.** Paper no. 17, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979

A80-24094#

As a contribution to the investigation of the suitability of using cryogenic nitrogen as the test gas in a high Reynolds number transonic wind-tunnel, a study is made of the real gas effects of nitrogen at low temperatures. The study, which is limited to inviscid, homentropic flow of a non-conducting gas, takes the form of an independent confirmation of results by Kilgore, et al. The new contribution in this paper is that the use of a simplified equation of state enables an expression for enthalpy (and hence the terms in Bernoulli's equation) to be derived by analytic integration.

*Aerodynamics Department, R.A.E., Farnborough, Hampshire GU14 6TD, U.K.

110 *Inger, G. R.: ***Transonic Shock-Boundary Layer Interactions in Cryogenic Wind Tunnels.*** Paper no. 18, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24097#

Since the transonic aerodynamics of missiles and aircraft can be significantly influenced by shock wave — boundary layer interaction effects, these effects should be adequately simulated in cryogenic high Reynolds number wind tunnel experiments. In addition to flight Mach and Reynolds numbers which are simulated by design, there are four other interaction similitude parameters which may not be duplicated owing to the very low temperature — high pressure working fluid involved: wall to total temperature ratio T_w/T_t, specific heat ratio γ, viscosity temperature exponent ω and Prandtl number Pr. The first is deemed especially important since in some proposed short duration cryogenic transonic wind tunnels the model is at much higher temperature than T_t during the test. Moreover, the γ of cryogenic nitrogen can be larger (1.5–1.8) than air and thus influence the interaction; lower γ's are also of interest in heavy gas (Freon 12) facilities. This paper describes the application of an approximate non-asymptotic theory of weak normal shock nonseparating turbulent boundary layer interaction to the prediction of these heat transfer and real gas effects.

*Virginia Polytechnic Institute and State University, Blacksburg, VA, 24060

111 *Smith, David A.: **Development of a Test Procedure for Acoustically Dissipative Silencer Materials Used in Cryogenic Applications.** Paper no. 19, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24098#

The objective of the test procedure discussed is to guide selection of optimum mechanical properties of acoustically dissipative materials to be used in silencers for cryogenic applications. The items of primary concern are: erosion of materials due to grazing flow, fatigue of materials due to grazing flow and intense sound pressure levels; and thermal shock of materials due to cryogenic temperatures. The proposed test procedure quantifies the degradation of mechanical properties of acoustically dissipative materials intended for use in an intense acoustic field, with flow, at cryogenic temperatures.

*General Acoustics Corp., 12248 Santa Monica Blvd., Los Angeles, CA, 90025

112 *North, R. J.: **The Cryogenic Technology Programme of the European Transonic Windtunnel Project.** Paper no. 20, 1st Int. Symp on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979

A80-24099#

The ETW project is concerned with the design and feasibility of a proposed large new European Transonic Windtunnel operating on the cryogenic principle. There are a number of problems to be solved in the design, construction and operation of such a tunnel. Amongst these problems are those of instrumentation, model design and construction, testing techniques, minimum operating temperature and so on. If it appears that there are basic difficulties in any of these areas the acceptability of the proposed tunnel to prospective users might be in doubt. Accordingly the Steering Committee of ETW has initiated a so-called cryogenic technology programme to examine these problems. A list of possible subjects of interest in a cryogenic technology programme is given. The present cryogenic technology programme is listed. A comparison of these lists shows that a combination of exchanges of information, an atmosphere of goodwill, and positive measures by the national representatives on the Steering Committee and by representatives of the aircraft industries has resulted in a program which covers a large part of the spectrum of interest.

*Technical Group, ETW, National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

113 *Haldeman, Charles W.: **Suggested Modification of Fog Flow Visualization for Use in Cryogenic Wind Tunnels.** Paper no. 21, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24100#

A mixture of liquid nitrogen and steam-bearing air has been used recently to produce flow visualization in a conventional subsonic wind tunnel. This note offers the suggestion that this technique might be modified to produce nitrogen "smoke" for flow visualization in cryogenic wind tunnels.

*Aerophysics Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 02139

114 *Morel, J. P.; and **Mereau, P.: **Optimum Control of the European Transonic Windtunnel.** Paper no. 22, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24102#

Analyses of ETW operating costs have shown the large influence of liquid nitrogen consumption during transients. Optimisation of control for ETW is desirable; it involves a theoretical and experimental programme during preliminary design so that, by the time of ETW construction, theoretical models checked through experiments will help in the design of control architecture. Interfaces between control and other tasks will be examined thoroughly. A simplified model has shown the highly-coupled aspect of ETW flow dynamics. Optimum control of the tunnel parameters Mach number, stagnation temperature, and stagnation pressure by use of the predictive algorithm IDCOM looks feasible based on some simulation on the simplified model. Preliminary results of the identification of Mach number process in the NLR HST shows that the validity of the use of the simplified model for control purposes looks promising in that field. More analysis is still required of test results obtained in the 1m×1m DFVLR and ONERA-CERT T'2 wind tunnels. A general model with less restrictive assumptions is being implemented on a computer. It must be checked with simplified model results as well as with the experimental tests. By the end of this preliminary design phase it is expected that use of theoretical models, validated by basic experiments, will give a first definition of an ETW control architecture.

*Technical Group, ETW, National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

**Adersa-Gerbios, Velizy, France

115 *Balakrishna, S.; and **Thibodeaux, J. J.: **Modeling and Control of a LN_2-GN_2 Operated Closed Circuit Cryogenic Wind**

Tunnel. Paper no. 23, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24103#

Full scale Reynolds number flow capability at transonic speeds has been successfully realized in wind tunnels by cooling the test gas to cryogenic temperatures. Gaseous nitrogen (GN_2) is an ideal cryogenic test medium because of its negligible thermal and caloritic imperfections on isentropic expansion, and since it can be cooled efficiently by injected liquid nitrogen (LN_2) which evaporates into the test gas. Despite increased gas density, cryogenic operation of a closed circuit wind tunnel is associated with reduced fan power and no extra dynamic loads on the models. Further, a closed circuit cryogenic tunnel allows independent control of the tunnel flow parameters. Precise control of these parameters is an involved control problem in view of the non-linear and coupled nature of the tunnel responses. This paper aims at developing a simple lumped parameter multivariable control compatible mathematical model of a LN_2-GN_2 operated closed circuit cryogenic tunnel, and deriving closed loop control laws with specific reference to the 0.3-m transonic cryogenic tunnel at the NASA Langley Research Center.

*Old Dominion University, Norfolk, VA, 23508

**NASA, Langley Research Center, Hampton, VA, 23665

NASA Grant NSG-1503

116 *Clausing, A.M. **Experimental Studies of Forced, Natural and Combined Convective Heat Transfer at Cryogenic Temperatures.** Paper no. 24, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr 3-5, 1979.

A80-24104#

A novel heat transfer technique, the use of cryogenic temperatures for convective modeling, is used in this study to obtain significant increases in $\rho^2\beta/\mu^2$ and ρ/μ, in order to simultaneously obtain large Grashof and Reynolds numbers on a vertical cylinder. The research is motivated by the need to predict combined convective losses from large, high-temperature objects such as solar "power tower" receivers where the magnitudes of both the Grashof and Reynolds numbers are large. The cryogenic heat transfer tunnel provides an economical method of obtaining these large Grashof and Reynolds numbers with an appropriate and near constant Prandtl number; thus it is an excellent tool for study of convective heat transfer. Low-temperature modeling, a cryogenic testing facility, and a transient measurement technique are discussed.

*University of Illinois at Urbana-Champaign, Urbana, IL, 61801

117 *Christophe, Jean; and *Francois, Gilbert: **Thermal Insulation of Pressurized Cryogenic Wind Tunnels.** Paper no. 25, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24105#

The transformation of existing wind tunnels for cryogenic operation requires an internal insulation to protect the walls, which usually are made of carbon steel, and are brittle at low temperatures. In order not to alter the shape of the aerodynamic circuit, a thin insulation is used that is efficient for a limited time only. A comparison of solutions with thick internal or external insulators allowed the study of the wall temperature evolution and of the energies implied during transient or permanent operations for long duration runs of several minutes to several tens of minutes. This paper presents a few remarks on the insulation of a wind tunnel with a view to its use down to 120 K. This fan driven wind tunnel, still under construction, will have a test section area of 0.15×0.35 m, a maximum stagnation pressure of 5 bars and a maximum velocity of Mach 1.0. Initially designed for operation at room temperature, it is now being modified for operation at cryogenic conditions. To this end, the main circuit is being built in stainless steel Z2CN 18-10 (the American 304 L). Provisions are planned for injection and evacuation of nitrogen and for thermal insulation.

*ONERA/CERT BP 4025, 31055 Toulouse Cedex, France

118 *Green, J.E.; *Weeks, D.J.; and *Pugh, P.G.: **Heat Transfer to Model or Test Section as a Source of Spurious Aerodynamic Effects in Transonic Wind Tunnels.** Paper no. 26, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24106#

For predictions of aerodynamic characteristics to be reliable, correct simulation of the thermal behaviour at full scale is essential. That is to say, the ratio of surface temperature to free-stream temperature may be expected to be just as important a parameter as Reynolds number in any flow in which boundary layer behaviour has a significant effect to the overall aerodynamics. The relative importance of Reynolds number and of heat transfer to the model is assessed in this paper on the basis of calculations of the flow over an aerofoil at subsonic and transonic speeds. The significance of heat transfer to the test-section walls is also assessed. Hence allowable temperature limits are suggested for both the model and the tunnel walls. The source of the results quoted here is a paper which was written in 1973 at the behest of the AGARD LaWs Group but given only limited circulation at that time. Whilst the theoretical methods used, particularly for the inviscid parts of the aerofoil calculations, have now been superseded by appreciably improved methods there is no reason to suppose that the use of these later methods would significantly alter our main conclusions.

*Royal Aircraft Establishment, Farnborough, Hampshire GU14 6TD, U.K.

119 *Mignosi, A.; and *Archambaud, J. P.: **Prediction of Thermal Losses and Transient Flows in a Cryogenic Wind Tunnel.** Paper no. 27, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24107#

In parallel with the experimental studies developed in a cryogenic pilot wind-tunnel called T2 which is induction driven, theoretical methods have been developed. This wind tunnel is used to give experimental data related with cryogenic problems. Prediction methods have been established to compute thermal losses, wind tunnel performance, and transient flows. These methods have been checked with experimental data and are used to predict and to optimize the wind tunnel flow. The contemplated application of these methods is a cryogenisation of our induction driven wind tunnel T2 (test section 0.4×0.4 m) in which great values of Reynolds number could be obtained.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

120 *Ray, Edward J.; *Ladson, Charles L.; *Adcock, Jerry B.; *Lawing, Pierce L.; and *Hall, Robert M.: **Review of Design and Operational Characteristics of the 0.3-Meter Transonic Cryogenic Tunnel.** Paper no. 28, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979. Also NASA TM-80123

A80-24108#

The past six years of operation with the NASA Langley 0.3-m Transonic Cryogenic Tunnel (TCT) has shown that there are no insurmountable problems associated with cryogenic testing with gaseous nitrogen at transonic Mach numbers. The fundamentals of the concept have been validated both analytically and experimentally and the 0.3-m TCT, with its unique Reynolds number capability, has been used for a wide variety of aerodynamic tests. Techniques regarding real-gas effects have been developed and cryogenic tun-

nel conditions can be set and maintained accurately. It has been shown that cryogenic cooling by injecting nitrogen directly into the tunnel circuit imposes no problems with temperature distribution or dynamic response characteristics. Experience with the 0.3-m TCT has, however, indicated that there is a significant learning process associated with cryogenic, high Reynolds number testing. Many of the questions have already been answered; however, factors such as tunnel control, run logic, economics, instrumentation, and model technology present many new and challenging problems.

*NASA, Langley Research Center, Hampton, VA 23665

121 *Richards, B. E. and *Wendt, J. F. **Preliminary Design Study of a Regeneratively-Cooled Transonic Cryogenic Tunnel.** Paper no. 29, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24109#

The cost of liquid nitrogen dominates the operating expenses of a cryogenic tunnel, particularly in the high speed range. To reduce this cost, a number of short-duration designs have been studied; many of them will be discussed at this symposium. One idea which does not seem to have received serious attention is the regeneratively-cooled concept. The purpose of this short paper is to present the concept for constructive criticism.

*von Karman Institute for Fluid Dynamics, Chaussée de Waterloo, 72, B-1640 Rhode-Saint-Genèse, Belgium

122 *Lambourne, N. C.: **Synopsis of Similarity Requirements for Aeroelastic Models in Cryogenic Wind Tunnels.** Paper no. 30, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24110#

A consideration of the requirements for aeroelastic similarity shows the low working temperature of a cryogenic tunnel and an ability to vary temperature both have advantages in regard to the choice of suitable stiffness and density scales for an aeroelastic model. The advantages are incidental to the main purpose of a cryogenic tunnel, which is to achieve high Reynolds numbers.

*Royal Aircraft Establishment, Bedford MK41 6AE, U.K.

123 *Gravelle, Alain: **Aeroelastic Models for Cryogenic Wind Tunnels.** Paper no. 31, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979. ONERA TP-1979-39, 1979.

A79-39088#

The application of Mach and Froude similarity rules to cryogenic wind tunnel testing of aeroelastic models is examined. It is shown that when stagnation temperatures are low and can be varied over a wide range, it is possible to obtain reasonable values for static loads and Reynolds numbers with flutter models. The scaling of models of the Airbus A300B and the F1 fighter for testing in a S2-MA wind tunnel is discussed and compared with possible scalings of similar models for testing in a cryogenic facility.

*ONERA, BP 72, 92322 Chatillon Cedex, France

124 *Ferris, Alice T.: **Cryogenic Wind Tunel Force Instrumentation.** Paper no. 32, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979. Also NASA TM-81845.

A80-24081#

A cryogenic wind tunnel imposes rather severe requirements on the measurement of aerodynamic forces and moments. Not only does the cryogenic environment present an unusual surrounding for the force balance, but also, because of the tunnel's high density capability, the magnitude of the load to be measured can be much greater than that of a conventional tunnel of the same size. Although pushing the state of the art, initial studies indicate that one-piece, high-capacity strain-gage balances can be built to satisfy cryogenic requirements. This paper will outline the work that has been accomplished at Langley Research Center while investigating the effects of the cryogenic environment on one-piece multicomponent strain-gage balances, with particular emphasis on cryogenic balances for use in the National Transonic Facility (NTF), a 2.5-m cryogenic facility that is being constructed at the National Aeronautics and Space Administration (NASA), Langley Research Center (LaRC), Hampton, VA. The NTF is scheduled to begin operation in mid-1982. One-piece multicomponent strain-gage balances have been designed to meet the requirements imposed by the cryogenic environment. These balances are a result of extensive studies in the areas of design, balance materials, strain gages (including application techniques), and cryogenic calibration. The laboratory results indicate that these balances will yield reliable, repeatable, and predictable data from 340 K to 77 K under steady-state conditions. Work is continuing in a number of areas to reduce the effect of the cryogenic environment even further where possible and to study the problems associated with thermal control that may be needed to eliminate thermal gradients.

*NASA, Langley Research Center, Hampton, VA, 23665

125 *Hill, Eugene G.: **The Proposed Boeing Supersonic Wind Tunnel High Reynolds Number Insert.** Paper no. 33, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24089#

Modification of the infrequently used Boeing Supersonic Wind Tunnel (BSWT) to provide high Reynolds number testing capabilities has been under study since 1974. Operating the modified four foot tunnel at cryogenic temperatures produces full scale Reynolds number with approximately 0.02 scale models. Current plans are to continue a low budget circuit development effort and to monitor progress in cryogenic wind tunnel testing technology. Non-cryogenic circuit development studies are scheduled for completion by the end of 1979. Subsequently, cryogenic circuit development studies in the 0.10 scale BSWT/BHRT pilot facility will continue during 1980. Limited studies are continuing to define the modifications required to convert the Boeing Supersonic Wind Tunnel into a high Reynolds number tunnel, BHRT. Many of the non-cryogenic modifications have been defined. Studies concerning cryogenic operations will begin late in 1979.

*Boeing Co., Box 3707, Seattle, WA, 98124

126 *Cadwell, J. D.: **Design, Fabrication, and Instrumentation Preparation of a Verification Model for the Douglas Aircraft Four Foot Cryogenic Wind Tunnel (4-CWT).** Paper no. 34, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24111#

The advent of the cryogenic work at the NASA Langley Research Center presented the technique that would allow the McDonnell Douglas Corporation to obtain a high Reynolds number transonic facility with reasonable dynamic pressures for a moderate capital expenditure. Although NASA had a continuous flow cryogenic pilot tunnel in operation, the blowdown concept had not been checked experimentally. Prior to approval of the capital expenditure an inhouse study was accomplished and verified in an independent feasibility study accomplished by the Fluidyne Corporation. Management approval to proceed with the modification of the existing four foot transonic tunnel to a four foot cryogenic tunnel (4-CWT) was given in mid 1976. The purpose of this report is to review the work accomplished to date on the design, fabrication,

and instrumentation of the DC-10 model to be used in the verification test of the McDonnell Douglas four foot Cryogenic Transonic Wind Tunnel.

*Douglas Aircraft Co., McDonnell Douglas Corp., 3855 Lakewood Blvd., Long Beach, CA 90846

127 *Aldrich, J. F. L.: **Progress Report on the Douglas Four-Foot Cryogenic Wind Tunnel.** Paper no. 35, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24086#

The Douglas design effort toward a cryogenic operating mode of their intermittent 4-ft wind tunnel began in August 1976 under the leadership of NASA Langley. The preliminary study had concluded that it was feasible, that the cost was reasonable for the Reynolds number gain, but that certain scaled tests should be conducted to minimize risks. The experimental program conducted is summarized. The design of the modifications on the 4-Foot Cryogenic Wind Tunnel (4CWT) began with the completion of the 1-Foot Cryogenic Wind Tunnel (1CWT) design and continued in parallel with the experimental program. About 85 percent of the design has been completed. Approximately 165 drawings have been released. The remaining design work includes stings, calibration equipment, control sensor installation and interconnections to operating console and computer. The majority of the supplier-fabricated items have been delivered. Modifications and installation work by the contractors is expected to be completed in August, at which time prerun checkout of the tunnel subsystems will begin and build up to check runs of the total system at ambient and cryogenic temperatures about October.

*Douglas Aircraft Co., McDonnell Douglas Corp. 3855 Lakewood Blvd., Long Beach, CA, 90846

128 *Clark, P. J. F.; and **Morel, J. P.: **Circuit Optimization Study for the European Transonic Windtunnel.** Paper no. 36, 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979.

A80-24101#

An Airline Optimization Study defines the most economical circuit configuration for the European Transonic Wind Tunnel (ETW) based on the combination of capital and operating costs consistent with flow quality, test spectrum and operational flexibility requirements. This study included investigations of the sensitivity of the optimum configuration to variations in the factors which affect the cost of the various components or cost elements over a reasonable range.

*DSMA International Inc., Toronto, M8X 1Y4 Canada

**Technical Group, ETW, National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

129 *Hall, Robert M.: **Onset of Condensation Effects With an NACA 0012-64 Airfoil Tested in the Langley 0.3-Meter Transonic Cryogenic Tunnel.** NASA TP-1385, Apr. 1979. 72 pp. Formerly published as NASA TM-78666.

N79-22043#

A 0.137-m NACA 0012-64 airfoil has been tested at a 0° angle of attack in the nitrogen-gas Langley 0.3-m Transonic Cryogenic Tunnel at free-stream Mach numbers of 0.75, 0.85, and 0.95 over a total pressure range from 1.2 to 5.0 atm. The onset of condensation effects as determined by varying stagnation temperature was found to correlate better with the amount of super-cooling in the free stream than it did with the supercooling in the region of maximum local Mach number over the airfoil. Effects in the pressure distribution over the airfoil were generally seen to appear over its entire length at nearly the same total temperature. Both observations suggest that heterogeneous nucleation does occur in the free stream. The present results are compared to calculations made by Sivier and data gathered by Goglia. The potential operational benefits realized from supercooling are presented in terms of increased Reynolds number capability at a given tunnel total pressure and reduced drive-fan power and liquid nitrogen consumption if Reynolds number is held constant. Depending on total pressure and free-stream Mach number, these three benefits are found to vary respectively from 8 to 19 percent, 12 to 24 percent, and 9 to 19 percent. An appendix is included which gives details of the data analysis and error estimates for the differences in pressure distributions.

*NASA, Langley Research Center, Hampton, VA, 23665

130 *Albone, C. M.: **An Investigation Into the Real Gas Effects of Cryogenic Nitrogen in Inviscid Homentropic Flow.** R.A.E. TM Aero 1805, May 1979. 17 pp.

N80-21611#

As a contribution to the investigation of the suitability of using cryogenic nitrogen as the test gas in a high Reynolds number transonic wind-tunnel, a study is made here of the real gas effects of nitrogen at low temperatures. The study, which is limited to inviscid, homentropic flow of a non-conducting gas, takes the form of an independent confirmation of results by Kilgore et al. A recent paper by Wagner and Schmidt on this subject employs a different equation of state from that used here and their investigations cover more than just homentropic flow. The new contribution in this Memorandum is that the use of a simplified equation of state enables an expression for enthalpy (and, hence, the terms in Bernoulli's equation) to be derived by analytic integration.

*Royal Aircraft Establishment, Farnborough, Hampshire GU14 6TD, U.K.

Note: A shortened version of this Memorandum (no. 109 in this bibliography) was presented at the First International Symposium on Cryogenic Wind Tunnels at Southampton University, Apr. 3-5, 1979.

131 *Hall, Robert M.: **Onset of Condensation Effects as Detected by Total Pressure Probes in the Langley 0.3-Meter Transonic Cryogenic Tunnel.** NASA TM-80072, May 1979. 51 pp.

N79-27094#

Total pressure probes mounted in the test section of the Langley 0.3-m Transonic Cryogenic Tunnel are used to detect the onset of condensation effects for free-stream Mach numbers of 0.50, 0.75, 0.85, and 0.95 and for total pressures between one and five atmospheres. The amount of supercooling is found to be about 3 K and suggests that condensation is occurring on pre-existing liquid nitrogen droplets resulting from incomplete evaporation of the liquid nitrogen injected to cool the tunnel. The liquid nitrogen injection process presently being used for the 0.3-m tunnel results in a wide spectrum of droplet sizes being injected into the flow. Since the relatively larger droplets take much more time to evaporate than the more numerous smaller droplets, the larger ones reach the test section first as the tunnel operating temperature is reduced. However, condensation effects in the test section are not immediately measurable because there is not a sufficient number of the larger droplets to have an influence on the thermodynamics of the flow.

*NASA, Langley Research Center, Hampton, VA, 23665

132 *Bursik, J. W., **Hall, R. M., and **Adcock, J. B.: **A Two-Phase Mach Number Description of the Equilibrium Flow of Nitro-**

gen in Ducts. AIAA 14th Thermophysics Conference, June 4-9, 1979, in Orlando, Florida.

AIAA 79-1051 A79-38034#

For equilibrium two-phase flow the squared ratio of mixture specific volume to mixture sound speed, $\beta(g,T)$ is shown to have the same form as many weighted mean two-phase properties; namely $\beta(g,T) = g\beta(1,T) + (1 - g)\beta(O,T)$ where g is the liquid mass fraction and $\beta(1,T)$ and $\beta(O,T)$ are the isothermal saturated liquid and vapor values of β which are generated for nitrogen in tabulated form by a computer program. With these β-tables a simplified method of calculating two-phase Mach numbers is developed for various duct flows. One- and two-phase Mach number jumps at phase boundaries are also discussed.

*Rensselaer Polytechnic Institute, Troy, NY, 12181

**NASA, Langley Research Center, Hampton, VA, 23665

133 *Ray, Edward J.; *Ladson, Charles L.; *Adcock, Jerry B.; *Lawing, Pierce L.; and *Hall, Robert M.: **Review of Design and Operational Characteristics of the 0.3-Meter Transonic Cryogenic Tunnel.** NASA TM-80123, Sept. 1979, 56 pp. Also presented at the 1st Int. Symp. on Cryogenic Wind Tunnels, Southampton, U.K., Apr. 3-5, 1979. (No. 120 in this bibliography.)

N79-32159#

The past 6 years of operation with the NASA Langley 0.3-m Transonic Cryogenic Tunnel (TCT) show that there are no insurmountable problems associated with cryogenic testing with gaseous nitrogen at transonic Mach numbers. The fundamentals of the concept were validated both analytically and experimentally and the 0.3-m TCT, with its unique Reynolds number capability, was used for a wide variety of aerodynamic tests. Techniques regarding real-gas effects were developed and cryogenic tunnel conditions can be set and maintained accurately. Cryogenic cooling by injecting liquid nitrogen directly into the tunnel circuit imposes no problems with temperature distribution or dynamic response characteristics. Experience with the 0.1-m TCT indicates that there is a significant learning process associated with cryogenic, high Reynolds number testing. Many of the questions have already been answered; however, factors such as tunnel control, run logic, economics, instrumentation, and model technology present many new and challenging problems.

*NASA, Langley Research Center, Hampton, VA, 23665

134 *Goodyer, M. J.: **Cryogenic Wind Tunnel Activities at the University of Southampton.** NASA CR-159144, Sept. 1979, 10 pp.

N80-10231#

The characteristics and behavior of a 0.1-m transonic cryogenic wind tunnel are discussed. The wide band of usable Reynolds numbers is analyzed along with a flow visualization technique using propane. The combination of magnetic suspension with the cryogenic wind tunnel is described. An outline of the circuit showing the locations of the magnet system and the features of the tunnel are presented.

*The University, Southampton SO9 5NH, Hampshire, U.K.

NASA grant NSG-7523

135 **Cryogenic Technology.** NASA CP-2122, Parts I and II, Mar. 1980, 441 pp.

N82-20357# (Pt. I)
N82-20358# (Pt. II)

The proceedings of this NASA conference, held in November 1979, contain 29 papers which address different engineering problems associated with the design of mechanisms and systems to operate in a cryogenic environment. The focal point for the entire engineering effort was the design of the National Transonic Facility, which is a closed-circuit cryogenic wind-tunnel. The papers covered a variety of subjects including thermal structures insulation systems, noise, seals, controls, instrumentation, and materials. Papers also addressed design, fabrication, and instrumentation problems for models to be tested in a cryogenic medium. The general areas covered by sessions were (1) Overviews, (2) Mechanical/Structural Design, (3) Systems Design, (4) Instrumentation, and (5) Model/Sting Technology. Selected items follow in this bibliography.

136 *Kilgore, Robert A.: **Evolution of the Cryogenic Wind Tunnel and Experience With the Langley 0.3-m Transonic Cryogenic Tunnel.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar. 1980, pp. 3-48. (Presented Nov. 1979.)

N82-20357# (pp. 3-48)

This paper traces some of the key events in the evolution of the cryogenic wind tunnel leading up to the decision in the United States to build the National Transonic Facility (NTF), the first major wind tunnel especially designed to take advantage of cryogenic operation. The NTF, which is the subject of this conference, will not only close the Reynolds number gap, but will also provide for the exploitation of other unique research capabilities made possible by cryogenic operation. A brief overview is given of the cryogenic wind tunnel projects around the world in order to illustrate the profound impact the cryogenic tunnel concept is having on wind tunnel development. This paper also reviews some of our experiences with the Langley 0.3-m Transonic Cryogenic Tunnel (TCT), the tunnel in which the cryogenic wind tunnel concept was verified at transonic speeds, thereby making possible the decision to build the NTF.

*NASA, Langley Research Center, Hampton, VA, 23665

137 *Howell, Robert R.: **Overview of Engineering Design and Operating Capabilities of the National Transonic Facility.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar. 1980, pp. 49-75. (Presented Nov. 1979.)

N82-20357#(pp. 49-75)

An overview of the engineering design of the National Transonic Facility is presented. The overview includes a summary of the design goals and criteria, pertinent design details and the projected facility performance. The facility will afford the nation a markedly improved capability to test at, or near, full scale Reynolds number and to assess the effects of Reynolds number, Mach number, and model deformation on the aerodynamics of configurations.

*NASA, Langley Research Center, Hampton, VA, 23665

138 *Bower, Robert E.: **Use of the National Transonic Facility as a National Testing Facility.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar. 1980, pp. 79-92. (Presented Nov. 1979.)

N82-20357#(pp. 79-92)

Special capabilities of the NTF are reviewed to encourage potential users to start planning for future tests. Specific areas of research and development are suggested. User concerns such as tunnel productivity, data quality, and procedures for proposing specific experiments are discussed. Participation by the scientific community in this opportunity for transonic research is encouraged, and mechanisms for implementation are offered.

*NASA, Langley Research Center, Hampton, VA, 23665

139 Entry 139 has been deleted.

140 *Mershon, Frank E. **Overview of Structural and Mechanical Session.** *Cryogenic Technology*, NASA CP-2122, Pt. 1, Mar 1980, 5 pp (Presented Nov 1979.)

N82-20357#(pp 95-99)

The Langley 0.3-m Transonic Cryogenic Tunnel and the National Transonic Facility have been described previously in this conference. This session will show examples of how the temperature range of the tunnel gas, 78K to 353K (140°R to 635°R), affected the design and development of structural and mechanical components, and will provide a detailed description of four major developmental areas.

*NASA, Langley Research Center, Hampton, VA 23665

141 *Ramsey, James W., Jr. **Design for Thermal Stress.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar 1980, pp 101-119 (Presented Nov 1979.)

N82-20357#(pp 101-119)

The large cryogenic wind tunnel structures inside the National Transonic Facility (NTF) were analyzed and designed for mechanical plus thermal stresses. The MITAS and SPAR computer programs were utilized to solve the large, forced convection (up to a 700 to 1 ratio) driven, thermal stress problem. To prevent overstressing, yielding, and fatiguing, structural criteria were developed. All requirements from the criteria imposed on these structures have been exceeded. An analysis and design procedure was developed with two large internal structures used to demonstrate this procedure. Several design approaches to reduce high thermal stresses are presented.

*NASA, Langley Research Center, Hampton, VA 23665

142 *Lassiter, William S. **Noise Attenuation in a Pressurized, Cryogenic Environment.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar 1980, pp 121-137 (Presented Nov 1979.)

N82-20357#(pp. 121-137)

Tests at ambient and cryogenic temperatures showed that the adhesive material used to bond the resonator system together retained shear, tensile, and fatigue properties at cryogenic temperatures. An attenuation test resulted in good agreement between experiment and theory in determining the attenuation of a prototype dual resonator panel.

*NASA, Langley Research Center, Hampton, VA 23665

143 *Joplin, Sammie D. **Status Report on Development of Large Seals for Cryogenic Applications.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar 1980, pp. 139-155 (Presented Nov. 1979.)

N82-20357#(pp. 139-155)

Several parameters have been identified that influence seal performance including surface finish, spring and pressure activation, seal fit in the groove, and treatments to the sealing surface with polymer tapes. Tests are in progress to establish the seal performance with lubricants, with bonded joints, and for a radial installation. Tests will also be made to establish that the seals will seal at cryogenic temperatures and will seal variable gaps during a thermal cycle.

*NASA, Langley Research Center, Hampton, VA 23665

144 *Wingate, Robert T. **Design of Compressor Fan Disks for Large Cryogenic Wind Tunnels.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar 1980, pp 157-176 (Presented Nov 1979)

N82-20357#(pp 157-176)

A number of general practical design considerations in the design of a large fan disk for a transient cryogenic environment arose out of the National Transonic Facility (NTF) fan disk design studies. Highlights of these considerations including design philosophy and factors influencing the geometry or external profile are discussed. Specific features of the NTF fan disk design are also presented as an example of a compromise design resulting from tradeoffs between these competing factors.

*NASA, Langley Research Center, Hampton, VA 23665

145 *Bruce, Walter E., Jr. **Systems Design Session — Overview.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar 1980, pp 179-184 (Presented Nov 1979.)

N82-20357#(pp 179-184)

The previous paper by Mr. R. R. Howell entitled "Overview of Engineering Design and Operating Capabilities of the National Transonic Facility" presented an overview of the various systems of the tunnel and described the basic operations of each. In this session, the focus will be on the systems designed to control fluids and energy which are affected by the cryogenic test gas and/or the cryogenic operation of the tunnel.

*NASA, Langley Research Center, Hampton, VA 23665

146 *Watson, Nathan D., and *Williams, Dave E. **Development of an Internal Thermal Insulation System for the National Transonic Facility.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar 1980, pp 185-221 (Presented Nov 1979.)

N82-20357#(pp 185-221)

This paper presents the results of a design effort to provide a cost effective and reliable insulation system for the pressure shell of the National Transonic Facility (NTF). Critical factors affecting the choice of internal insulation instead of an external insulation system are discussed. Design criteria established for the internal insulation system are presented.

*NASA, Langley Research Center, Hampton, VA 23665

147 *Kelsey, Eugene L., and *Turner, Robert D. **Connectors and Wiring for Cryogenic Temperatures.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar 1980, pp. 223-233 (Presented Nov 1979.)

N82-20357#(pp 223-233)

Electrical connectors and wiring insulation exposed to cyclic cryogenic thermal environment are subject to cyclic stresses which can lead to cracking and failure of these components. This paper describes a series of tests which were implemented to qualify connectors and wiring for the transient thermal environment of the National Transonic Facility at NASA's Langley Research Center.

*NASA, Langley Research Center, Hampton, VA 23665

148 *Kirby, Cecil E. **Status of Mathematical Modeling of National Transonic Facility Fluid Dynamic Processes.** Cryogenic Technology, NASA CP-2122, Pt. I, Mar 1980, pp 235-247 (Presented Nov 1979.)

N82-20357#(pp 235-247)

The theoretical basis of the four different approaches being used for mathematical modeling of the National Transonic Facility (NTF) are summarized in this paper along with results of limited experimental verification tests. Qualitative discussions are presented on the fan and plenum/slotted-wall test section performance and cross coupling effects between temperature, pressure, and Mach number. Calculated results from the computer model for commanded changes in set points are also presented.

*NASA, Langley Research Center, Hampton, VA 23665

149 *Osborn, James A. **A Descripton of the National Transonic Facility Process Control System.** Cryogenic Technology. NASA CP-2122, Pt. I, Mar. 1980, pp. 249-258 (Presented Nov. 1979)

N82-20357#(pp. 249-258)

High productivity and energy efficiency have been emphasized in the design of the National Transonic Facility. To support these goals a three level hierarchial control system has been designed to provide fast response, flexibility, and automation. The control system utilizes dedicated analog controllers, individual digital microcomputers, and a large supervisory computer. Standard commercial hardware is used throughout.

*NASA, Langley Research Center, Hampton, VA. 23665

150 *Buckley, John D., and *Sandefur, Paul G., Jr. **Development of Joining Techniques for Finned Tube Heat Exchanger for a Cryogenic Environment.** Cryogenic Technology. NASA CP-2122, Pt. I, Mar. 1980, pp. 259-269 (Presented Nov. 1979)

N82-20357#(pp. 259-269)

Three joining methods were considered for use in fabricating cooling coils for the National Transonic Facility. Results of evaluation tests are presented.

*NASA, Langley Research Center, Hampton, VA. 23665

151 *Ivey, George W., Jr. **Cryogenic Gaseous Nitrogen Discharge System.** Cryogenic Technology. NASA CP-2122, Pt. I, Mar. 1980, pp. 271-278 (Presented Nov. 1979)

N80-20357#(pp. 271-278)

A discharge system for dispersing the gaseous nitrogen exhaust of the NTF into the atmosphere is described.

*NASA, Langley Research Center, Hampton, VA. 23665

152 *Guarino, Joseph F. **Instrumentation Systems for the National Transonic Facility — Overview.** Cryogenic Technology. NASA CP-2122, Pt. II, Mar. 1980, pp. 281-286 (Presented Nov. 1979)

N82-20358#(pp. 281-286)

Intrumentation and measurement systems are important elements in any complex research facility. The National Transonic Facility with its unique operational characteristics is clearly a complex facility and as such represents a significant challenge to wind tunnel instrument designers. This paper will briefly describe the instrument requirements imposed by the new testing environment, the instrument systems being provided for facility calibration and operation, and the research and development activities directed at meeting overall instrument and measurement requirements.

*NASA, Langley Research Center, Hampton, VA. 23665

153 *Bryant, Charles S. **The National Transonic Facility Data System Complex.** Cryogenic Technology. NASA CP-2122, Pt. II, Mar. 1980, pp. 287-297 (Presented Nov. 1979)

N82-20358#(pp. 287-297)

The National Transonic Facility Data System Complex will be composed of four central processing units configured in a fully connected, distributed network. Each of the four computer systems in this network and the associated analog and digital data acquisition, recording, control, and display equipment are described and functional capabilities outlined.

*NASA, Langley Research Center, Hampton, VA. 23665

154 *Ferris, Alice T. **Cryogenic Wind Tunnel Force Instrumentation.** Cryogenic Technology. NASA CP-2122, Pt. II, Mar. 1980, pp. 299-315 (Presented Nov. 1979)

N82-20358#(pp. 299-315)

NASA LaRC has developed one-piece strain gage force balances for use in cryogenic wind tunnel applications. This was accomplished by studying the effect of the cryogenic environment on materials, strain gages, cements, solders, and moisture-proofing agents and selecting those that minimized strain gage output changes due to temperature. Wind tunnel results obtained from the Langley 0.3-m Transonic Cryogenic Tunnel were used to verify laboratory test results.

*NASA, Langley Research Center, Hampton, VA. 23665

155 *Mitchell, Michael. **Pressure Measurement System for the National Transonic Facility.** Cryogenic Technology. NASA CP-2122, Pt. II, Mar. 1980, pp. 317-327 (Presented Nov. 1979)

N82-20358#(pp. 317-327)

Over the last 4 years the Electronically Scaled Pressure (ESP) Measurement System has been developed at LaRC with the primary objective being to satisfy the pressure measurement requirements of the National Transonic Facility. The system is capable of making a large number of pressure measurements simultaneously. The ESP system has undergone an extensive field evaluation and the overall results show that the ESP system can make measurements within 0.25 percent of full scale in a liquid nitrogen environment provided the module is contained in a temperature controlled enclosure (currently under development), maintained at a constant temperature, and the system is calibrated immediately before each measurement. The system is also compatible with the distributed processing concept.

*NASA, Langley Research Center, Hampton, VA. 23665

156 *Finley, Tom D. **Model Attitude Measurements in the National Transonic Facility.** Cryogenic Technology. NASA CP-2122, Pt. II, Mar. 1980, pp. 329-341 (Presented Nov. 1979)

N82-20358#(pp. 329-341)

The National Transonic Facility has established a requirement for the precise measurement of model pitch and roll. Two approaches to this problem are being explored. The conventional approach to model attitude measurements at the Langley Research Center involves the use of precision accelerometers to detect the attitude of the model with respect to the local vertical. Testing has indicated that this technique can be used in the NTF with only a slight degradation in accuracy. A problem which persists when using accelerometers is that of response. The slow response of this type of measurement system has forced us to consider the use of an optical measurement system. A contract presently in effect calls for the study of the problems associated with using an interferometric angle measurement system in the NTF environment. This paper describes the work done to date on both these approaches.

*NASA, Langley Research Center, Hampton, VA. 23665

157 *Germain, Edward F. **Temperature Instrument Development for a Cryo Wind Tunnel.** Cryogenic Technology. NASA CP-2122, Pt. II, Mar. 1980, pp. 343-351 (Presented Nov. 1979)

N82-20358#(pp. 343-351)

The development work which extended conventional wind tunnel thermometry into the cryogenic wind tunnel range is reviewed. The emphasis is on stagnation temperature measurements where a mix of platinum resistance thermometers and thermocouples is necessary to satisfy all the requirements. Calibration and thermo-

couple homogeneity test equipment are described

*NASA, Langley Research Center, Hampton, VA, 23665

158 *Holmes, H. K.: **Model Deformation Measurements in the National Transonic Facility.** *Cryogenic Technology.* NASA CP-2122, Pt. II, Mar. 1980, pp. 353-361. (Presented Nov. 1979.)

N82-20358#(pp. 353-361)

Four measurement approaches are discussed: Stereo photogrammetry, scanning stereo photogrammetry, Moiré topography, and microwave modulated laser beams. Several problem areas which must be accommodated — sensor motion, target mounting, surface constraints, and computational complexities — have been identified.

*NASA, Langley Research Center, Hampton, VA, 23665

159 *Young, Clarence P., Jr.: **Cryogenic Models/Sting Technology Session — Overview.** *Cryogenic Technology,* NASA CP-2122, Pt. II, Mar. 1980, pp. 365-371. (Presented Nov. 1979.)

N82-20358#(pp. 365-371)

The advent of high Reynolds number, high dynamic pressure testing in a cryogenic environment offers exciting and difficult challenges for the researcher and model/sting systems design engineers. Although much experience has been obtained in the use of the Langley 0.3-m Transonic Cryogenic Tunnel, new technology is required for the design and fabrication of models/stings for testing at high Reynolds numbers and high pressures in the new National Transonic Facility. The technology activities reported in this overview are just getting underway at Langley Research Center and are expected to be a continuing effort until the NTF is operational. The papers selected for publication in this session of the proceedings represent the experience obtained to date and reflect the areas of work that are believed to be of primary interest to potential users of the National Transonic Facility.

*NASA, Langley Research Center, Hampton, VA, 23665

160 *McKinney, Linwood W.: **Considerations in the Selection of the Pathfinder Model Configurations.** Cryogenic Technology, NASA CP-2122, Pt. II, Mar. 1980, pp. 373-381. (Presented Nov. 1979.)

N82-20358#(pp. 373-381)

An advanced transport and a highly maneuvering fighter configuration have been selected as initial models for the cryogenic high dynamic pressure model technology development program. These models will provide a basis for establishing practical achievable Reynolds number boundaries based on model stresses and model/balance/sting system dynamics. The model loads, thus the stresses, will be constant in the NTF when matching full scale airplane Reynolds numbers over the altitude range at a constant load factor. The maximum Reynolds number obtainable under these conditions will be limited by the influence of dynamic pressure on model/balance/sting system dynamics. Reynolds numbers to 25 million, based on chord, can be obtained on the Pathfinder models in the NTF with no increase in loads over those encountered in existing tunnels. These models represent advanced technology configurations and will be used for parametric research studies.

*NASA, Langley Research Center, Hampton, VA, 23665

161 *Gloss, Blair B.: **Some Aerodynamic Considerations Related to Surface Definition.** Cryogenic Technology, NASA CP-2122, Pt. II, Mar. 1980, 383-393. (Presented Nov. 1979.)

N82-20358#(pp. 383-393)

The requirement for high quality National Transonic Facility test data and the high Reynolds number capability of the NTF have caused NASA to reexamine the areas of model fabrication tolerances, model surface finish, and orifice induced pressure error. The results of this reexamination and planned research programs to extend the data base are described in this paper.

*NASA, Langley Research Center, Hampton, VA, 23665

162 *Bradshaw, James F., and *Lietzke, Donald A.: **Pathfinder I Model.** Cryogenic Technology, NASA CP-2122, Pt. II, Mar. 1980, pp. 395-410. (Presented Nov. 1979.)

N82-20358# (pp. 395-410)

This paper describes the Pathfinder I Model that has been designed for testing in the National Transonic Facility. Unique considerations for the design of cryogenic models are discussed along with the particular design requirements for Pathfinder I. The geometric details of the model are provided and various features of the model components are discussed, along with a description of design validation test support activities. Also, data are presented which emphasize the importance of material selection as it influences the model test program because of material property changes with temperature. It is found that good engineering practice with proper consideration given to the cryogenic environment and specific test requirements will produce a model acceptable to testing in the National Transonic Facility.

*NASA, Langley Research Center, Hampton, VA, 23665

163 *Hunter, William F.: **Analysis and Testing of Model/Sting Systems.** Cryogenic Technology, NASA CP-2122, Pt. II, Mar. 1980, pp. 411-422. (Presented Nov. 1979.)

N82-20358#(pp. 411-422)

The analysis and testing approach for model/sting systems being designed for the National Transonic Facility at Langley Research Center is presented in this paper. Principal areas of analysis are discussed along with the development of mathematical models that are being employed for various analyses. The interrelation and importance of rigorous analysis and verification testing in the design of model/sting systems for cryogenic, high Reynolds number testing are emphasized. The ongoing analysis and verification testing applications to the design of the first developmental model, Pathfinder I, are described and some preliminary results are given.

*NASA, Langley Research Center, Hampton, VA, 23665

164 *Hudson, C. Michael: **Material Selection for the Pathfinder I Model.** Cryogenic Technology, NASA CP-2122, Pt. II, Mar. 1980, pp. 423-441. (Presented Nov. 1979.)

N82-20358#(pp. 423-441)

The extremely low wind-stream temperatures (approximately 78 K in the National Transonic Facility) can significantly reduce the fracture toughness of many of the materials which might be used in constructing wind-tunnel models. Conversely, high fracture toughness is essential for the first model to be tested in the NTF (the so-called Pathfinder I model) because the stresses in the vicinity of structural discontinuities are quite high. These high stresses, if applied to relatively low toughness materials, would result in unacceptably small critical flaw sizes. To preclude the possibility of developing such small critical flaws (which would be difficult to detect), a materials survey was conducted to determine which materials possessed adequate strength and toughness at 78 K (140° R) to be considered for model construction. The Fracture and Deformation Division of the National Bureau of Standards developed a preliminary list of candidate materials. NASA Langley personnel subsequently expanded this list to include several additional materials. NASA Langley personnel further developed a series of factors which governed the selection of the materials for model fabrication. These

factors included strength properties, fracture toughness, availability, corrosion resistance, machinability, cost, and delivery. The weldability of the material was not an important factor for this model since no structural welding will be done. This paper presents the results of the studies to select an optimum material for fabricating Pathfinder I.

*NASA, Langley Research Center, Hampton, VA, 23665

165 *Kilgore, Robert A.: **Development of the Cryogenic Tunnel Concept and Application to the U.S. National Transonic Facility.** Paper No. 2 in AGARDograph No. 240, "Towards New Transonic Windtunnels," Nov. 1979. 27 pp.

N80-19139#

Based on theoretical studies and experience with a low-speed fan-driven tunnel and with a pressurized transonic tunnel, the cryogenic wind-tunnel concept has been shown to offer many advantages with respect to the attainment of full-scale Reynolds number at reasonable levels of dynamic pressure in a ground-based facility. The unique modes of operation available in a pressurized cryogenic tunnel make possible for the first time the separation of Mach number, Reynolds number, and aeroelastic effects. By reducing the drive-power requirements to a level where a conventional fan-drive system may be used, the cryogenic concept makes possible a tunnel with high productivity and run times sufficiently long to allow for all types of tests at reduced capital costs and, for equal amounts of testing, reduced total energy consumption in comparison with other tunnel concepts. A new fan-driven high Reynolds number transonic cryogenic tunnel is now under construction in the United States at the NASA Langley Research Center. The tunnel, to be known as the National Transonic Facility (NTF), will have a 2.5 by 2.5m test section and will be capable of operating from ambient to cryogenic temperatures at stagnation pressures up to 8.8 atm. By taking full advantage of the cryogenic concept, the NTF will provide an order of magnitude increase in Reynolds number capability over existing tunnels in the United States.

*NASA, Langley Research Center, Hampton, VA, 23665

166 *Hartzuiker, J. P.; **Christophe, J.; ***Lorenz-Meyer, W.; and ****Pugh, P. G.: **The Cryogenic Windtunnel; Another Option for the European Transonic Facility.** Paper No. 3 in AGARDograph No. 240, "Toward New Transonic Windtunnels," Nov. 1979. 15 pp.

N80-19140#

A new option for the proposed European transonic wind tunnel is described: a cryogenic facility with test-section dimensions compatible with existing major European transonic facilities. The tunnel performance is to the functional specification of the LaWs Group (Reynolds number based on mean aerodynamic chord variable between 25×10^6 and 40×10^6). The advantages and drawbacks of cryogenic testing as well as fundamental aspects of cryogenic aerodynamics are discussed. Comparative estimates for capital and operating costs are presented.

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**ONERA, BP 72, 92322 Chatillon Cedex, France

***DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

****Royal Aircraft Establishment, Bedford MK41 6AE, U.K.

167 *Balakrishna, S.: **Synthesis of a Control Model for a Liquid Nitrogen Cooled, Closed Circuit, Cryogenic Nitrogen Wind Tunnel and its Validation.** Progress Rept., period ending Sept. 1979. NASA CR-162508, Nov. 1979. 142 pp.

N80-13058#

The details of the efforts to synthesize a control-compatible multivariable model of a liquid nitrogen cooled, gaseous nitrogen operated, closed circuit, cryogenic pressure tunnel are presented. The synthesized model was transformed into a real-time cryogenic tunnel simulator, and this model is validated by comparing the model responses to the actual tunnel responses of the 0.3-m Transonic Cryogenic Tunnel using the quasi-steady-state and the transient responses of the model and the tunnel. The global nature of the simple, explicit, lumped multivariable model of a closed circuit cryogenic tunnel is demonstrated.

*Old Dominion University, Norfolk, VA, 23508

NASA Grant NSG-1503

168 *Younglove, Ben; and *McCarty, R. D.: **Thermodynamic Properties of Nitrogen Gas Derived from Measurements of Sound Speed.** NASA RP-1051, Dec. 1979. 53 pp. Also NBSIR 79-1611.

N80-14257#

A virial equation of state for nitrogen has been determined by use of newly measured speed-of-sound data and existing pressure-density-temperature data in a multiproperty-fitting technique. The experimental data taken were chosen to optimize the equation of state for a pressure range of 0 to 10 atm and for a temperature range of 60 to 350 K. Comparisons are made for thermodynamic properties calculated both from the new equation and from existing equations of state.

*National Bureau of Standards, Boulder, CO, 80302

Funded by NASA Langley Research Center, Hampton, VA

169 *Johnson, W. G., Jr.; and *Igoe, W. B.: **Aerodynamic Characteristics at Low Reynolds Numbers of Several Heat-Exchanger Configurations for Wind Tunnel Use.** NASA TM-80188, Dec. 1979. 54 pp.

N80-14046#

In response to design requirements of the National Transonic Facility, aerodynamic tests were conducted to determine the pressure-drop, flow-uniformity, and turbulence characteristics of various heat-exchanger configurations as a function of Reynolds number. Data were obtained in air with an indraft flow apparatus operated at ambient temperature and pressure. The unit Reynolds number of the tests varied from about 0.06×10^6 to about 1.3×10^6 per meter. The test models were designed to represent segments of full-scale tube bundles and included bundles of round tubes with plate fins in both staggered and inline tube arrays, round tubes with spiral fins, elliptical tubes with plate fins, and an inline grouping of tubes with segmented fins.

*NASA, Langley Research Center, Hampton, VA, 23665

170 *Mueller, M. H.; *Clausing, A. M.; *Clark, G. L., Jr.; *Weiner, J. G.; and *Kempka, S. N.: **Description of UIUC Cryogenic Wind Tunnel Including Pressure Distributions, Turbulence Measurements and Heat Transfer Data.** Univ. of Ill. Tech. Rept. ENG-79-4013, Dec. 1979. 91 pp.

N82-77683#

The UIUC cryogenic heat transfer tunnel is a recirculating type wind tunnel with a rectangular test section. Cooling is achieved by the use of liquid nitrogen, and the tunnel can be operated anywhere between 80 K and 300 K. Different types of tests were conducted in order to qualify the wind tunnel by comparing results obtained with well documented work. Results are given and discussed. Models

used are described. The wind tunnel proved to be a satisfactory means of studying heat transfer phenomena.

*University of Illinois at Urbana-Champaign, Urbana, IL, 61801

171 *Kilgore, Robert A.: **Wind Tunnel.** McGraw-Hill, 1979, Yearbook of Science and Technology, pp. 413-415.

A means for meeting the need for improved Reynolds number capability in wind tunnels has been provided at the NASA Langley Research Center in Hampton, Va., by the development of tunnels capable of operating at cryogenic temperatures, with minimum temperatures near 77 K (-321°F). Cooling the wind tunnel test gas to cryogenic temperatures results in a large increase in Reynolds number without raising dynamic pressure, while reducing the tunnel drive-power requirements. The cryogenic concept is explained and several small cryogenic wind tunnels are described. The largest cryogenic tunnel is the National Transonic Facility (NTF), under construction at the Langley Research Center, which will meet the high-Reynolds number testing needs of the U.S.A.

*NASA, Langley Research Center, Hampton, VA, 23665

172 *Blanchard, A., *Dor, J. B., and *Breil, J. F.: **Mesures des Fluctuations de Temperature et de Pression dans la Soufflerie Cryogenique T'2.** (Toulouse). Rept. No. OA8/5007 and DERAT No. 8,5007 DN, Jan. 1980, 22 pp. (English translation follows as the next entry.)

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

173 *Blanchard, A.; *Dor, J. B.; and *Breil, J. F.: **Measurements of Temperature and Pressure Fluctuations in the T'2 Cryogenic Wind Tunnel.** NASA TM-75408, Oct. 1980. 48 pp. Transl. by Kanner (Leo) Associates, Redwood City, CA. (For original French article, see the preceding entry in this compilation.)

N81-26158#

Cold wire measurements of temperature fluctuations were made in a DERAT T'2 induction powered cryogenic wind tunnel for 2 types of liquid nitrogen injectors. Thermal turbulence measured in the settling chamber depends to a great extent on the injector used; for fine spray of nitrogen drops, this level of turbulence seemed completely acceptable. Fluctuations in static pressure taken from the walls of the test section by Kulite sensors showed that there was no increase in aerodynamic noise during cryogenic gusts.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

NASA Contract NASw-3199

174 *Dinguirard, M.; *Serrot, G.; *Duffaut, J.; *Blanchard, A.; *Dor, J. B.; and *Breil, J. F.: **Etude Qualitative de l'Apparition du Brouillard d'Azote dans la Soufflerie Cryogenique a Induction T'2.** ONERA/CERT Rept. 1/6059, Feb. 1980. 73 pp. Translated into English by Kanner (Leo) Associates, Redwood City, CA. **Qualitative Study of the Appearance of Nitrogen Fog in the Cryogenic Induction Wind Tunnel T'2.** NASA TM-75857, Aug. 1980. 64 pp. (U.S. Gov't. Agencies and Their Contractors Only.)

X81-10353 (Translation)

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

175 *Howell, Robert R.: **The National Transonic Facility: Status and Operational Planning.** Presented at the AIAA 11th Aerodynamic Testing Conference, Denver, Colorado, Mar. 18-20, 1980. 9 pp.

AIAA Paper 80-0415 A80-26930#

The construction of the National Transonic Facility is advancing on schedule toward a target completion date in 1982. Several residual concerns remain which may emerge as problems in the operation of the facility. Among these are thermal stress constraints which may limit the rate at which temperatures can be changed, seal performance in a dynamic cryogenic environment which may result in undesirable internal flow leaks, and inadequate understanding of the detailed tunnel flow process which could result in inefficient process controls. The current design affords the capability of dealing with all of these concerns if they become problems. The outstanding instrument need is for a real time model surface deformation measurement system. A program for the development of this instrument system is underway. The user access to the National Transonic Facility has been addressed and a plan developed which will allow any qualified user access to the facility. The use of the NTF by organizations outside of NASA is encouraged. A practical look at the occupancy cost and the cost of liquid nitrogen for high Reynolds number tests indicates that operating costs should not be an inhibiting factor in the use of the NTF.

*NASA, Langley Research Center, Hampton, VA, 23665

176 *Thibodeaux, Jerry J., and **Balakrishna, S.: **Automatic Control of NASA Langley's 0.3-Meter Cryogenic Test Facility.** Presented at the AIAA 11th Aerodynamic Testing Conference, Colorado Springs, Colorado, Mar. 18-20, 1980. 15 pp.

AIAA Paper 80-0416 A80-26931#

Experience during the past 6 years of operation of the Langley 0.3-m Transonic Cryogenic Tunnel has shown that there are problems associated with efficient operation and control of cryogenic tunnels using manual control schemes. This is due to the high degree of process crosscoupling between the independent control variables (temperature, pressure, and fan drive speed) and the desired test condition (Mach number and Reynolds number). One problem has been the inability to maintain long-term accurate control of the test parameters. Additionally, the time required to change from one test condition to another has proven to be excessively long and much less efficient than desirable in terms of liquid nitrogen and electrical power usage. For these reasons, studies have been undertaken to (1) develop and validate a mathematical model of the 0.3-m cryogenic tunnel process, (2) utilize this model in a hybrid computer simulation to design temperature and pressure feedback control laws, and (3) evaluate the adequacy of these control schemes by analysis of closed-loop experimental data. This paper presents results of these studies.

*NASA, Langley Research Center, Hampton, VA, 23665

**Old Dominion University, Norfolk, VA, 23508

177 *Johnson, Charles B.: **A Study of Nonadiabatic Boundary-Layer Stabilization Time in a Cryogenic Tunnel for Typical Wing and Fuselage Models.** Presented at the AIAA 11th Aerodynamic Testing Conference, Colorado Springs, Colorado, Mar. 18-20, 1980. 9 pp.

AIAA Paper 80-0417 A80-26932#

A theoretical study has been made of the time varying effect of nonadiabatic wall conditions on boundary layer properties for a two-dimensional wing section and an axisymmetric body of revolution typical of a fuselage. The wing section and body of revolution are representative of the root chord and fuselage of what is considered to be a typical size transport model for the National Transonic Facility. The transient analysis was made at a Mach number of 0.85, for stagnation pressures of 2, 6, and 9 atm at several cryogenic values of total temperature for a solid wing and for three different fuselage skin thickness configurations. The analysis considered wing and fuselage sections made from stainless steel, beryllium copper, and aluminum. Examples are presented that may be used to determine the time required to reach an adiabatic condition after a change in total temperature.

*NASA, Langley Research Center, Hampton, VA, 23665

178 *Adcock, Jerry B.; and *Johnson, Charles B.: **A Theoretical Analysis of Simulated Transonic Boundary Layers in Cryogenic-Nitrogen Wind Tunnels.** NASA TP-1631, Mar. 1980. 37 pp.

N80-19131#

A theoretical analysis has been made to determine the real-gas effects on simulation of transonic boundary layers in wind tunnels with cryogenic nitrogen as the test gas. The analysis included laminar and turbulent flat-plate boundary layers and turbulent boundary layers on a two-dimensional airfoil. The results indicate that boundary layers in such wind tunnels should not be substantially different from ideal-gas boundary layers at standard conditions. At a pressure of 9.0 atm, two separate effects produce deviations of real-gas values from ideal-gas values which are in the opposite direction from deviations at 1.0 atm and are of the same insignificant order of magnitude. Results also show that nonadiabatic boundary layers should be adequately simulated if the enthalpy ratio is the correlating parameter rather than the temperature ratio.

*NASA, Langley Research Center, Hampton, VA, 23665

179 *Balakrishna, S.: **Automatic Control of a Liquid Nitrogen Cooled, Closed-Circuit, Cryogenic Pressure Tunnel.** Progress Report for the period Oct. 1979–March 1980. Submitted by the Old Dominion University Research Foundation, Norfolk, VA, NASA CR-162636, Mar. 1980. 97 pp.

N80-22366#

This report details the control analysis phase of the project "Modeling and Control of Transonic Cryogenic Wind Tunnels," sponsored by NASA Langley Research Center (LaRC). The contents of this document complement the modeling phase activity which has been reported as "Synthesis of a Control Model for a Liquid Nitrogen Cooled, Closed Circuit, Cryogenic Nitrogen Wind Tunnel and its Validation" (entry 167 in this compilation). This document reports the details of control law design, proof of its adequacy, microprocessor compatible software design, and electronic hardware realization and its successful performance on the 0.3-m Transonic Cryogenic Tunnel at NASA LaRC.

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NASA Grant NSG-1503

180 *Bald, W. B.: **A Discussion Document on the Thermal Design of Force Balances for Cryogenic Wind Tunnels.** Rept. no. OUEL-1321/80, Mar. 1980. 41 pp.

N81-24119#

The design performance, and theory of unheated and heated balances are reviewed. As extensive strain gage calibration is necessary for unheated balances, they are not considered as favorable as heated ones. Five heaters are utilized in the heated balance arrangement proposed. Their role is to compensate for conductive losses and to prevent and minimize convective losses. Finite element techniques are employed, details being given about the appropriate computer packages. The results of preliminary temperature measurements made on a TEM 1004/101 half balance are given, the outputs from the thermocouples used being fed via simple conditioning amplifiers into a U.V. recorder. The results indicate that further work is necessary to optimize design and performance.

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Contract no. AT/2057/072/XR/AERO

181 *Adcock, Jerry B.: **Simulation of Flat-Plate Turbulent Boundary Layers in Cryogenic Tunnels.** Journal of Aircraft, vol. 17, Apr. 1980. pp. 284-285.

A80-28855#

The magnitudes of real-gas effects on flat-plate turbulent boundary layer simulations in a cryogenic nitrogen wind tunnel are investigated in order to determine the validity of the method used by Inger (1979) to estimate real-gas effects. Boundary layer solutions for real gases, ideal gases with a specific heat ratio of 1.6 and ideal diatomic gases (specific heat ratio 1.4) were obtained for the worst case conditions of maximum stagnation pressure (9 atm), minimum stagnation temperature (120 K) and Mach number of 1.2. Calculated boundary layer parameters such as friction coefficient and displacement thickness are shown to agree closely for the real gas and the ideal diatomic gas (specific heat ratio 1.4), while the ideal gas solution used by Inger is shown to differ from the real-gas values considerably. Results indicate that real-gas effects on a flat-plate turbulent boundary layer simulation in a cryogenic nitrogen tunnel are insignificant, and suggest the unlikelihood of the large real-gas effects reported by Inger for turbulent boundary layer shock interactions.

*NASA, Langley Research Center, Hampton, VA, 23665

182 *Goodyer, M. J. (Lecture Series Director): **Cryogenic Wind Tunnels; AGARD/VKI Lecture Series 111.** Presented May 19-23, 1980, at Rhode-Saint-Genese, Belgium and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11048#

This Lecture Series is designed for engineers, including those experienced with conventional wind tunnels, wishing to acquire in a concentrated form the principles and practice of cryogenic wind tunnels. The emphasis is on the unfamiliar facets of technology which must be applied, and on solutions to special problems which arise from the exploitation of a low temperature test gas. Lectures provide up-to-date information on the aerodynamic and mechanical design of continuous and intermittent cryogenic wind tunnels and their models, and on techniques for controlling test parameters. Design information includes properties of materials, the storage and handling of cryogenic liquids, insulation systems for pipelines and tunnel circuits, and safety requirements. Solutions are included for the special requirements of instrumentation systems for plant, tunnel, and model. The physical processes will be described which determine the lower limits of operating temperature. The four major cryogenic wind tunnel projects for aeronautical testing are also described. Two of these being in the U.S.A. and two in Europe.

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Note: The Series was sponsored by the Fluid Dynamics Panel of AGARD and implemented by the von Karman Institute. Nineteen papers were presented and are listed immediately following this entry.

183 *Goodyer, M. J.: **Introduction to the Principles of Cryogenic Wind Tunnels with Outlines of Potential Applications.** Presented as Paper No. 1 at the AGARD/VKI Lecture Series 111, May 19-23, 1980 at Rhode-Saint-Genese, Belgium and May 27-30, 1980 at NASA Langley Research Center, Hampton, VA.

N81-11049#

*The University, Southampton SO9 5NH, Hampshire, U.K.

184 *Scurlock, R. G.: **Cryogenic Engineering I.** Presented as Paper No. 2 at the AGARD/VKI Lecture Series 111, May 19-23, 1980

at Rhode-Saint-Genese, Belgium and May 27-30, 1980 at NASA Langley Research Center, Hampton, VA.

N81-11050#

Subjects covered in this lecture include: basic properties of liquid nitrogen, oxygen, and air; and control of heat fluxes, insulation techniques, and low-loss storage.

*The University, Southampton SO9 5NH, Hampshire, U.K.

185 *Scurlock, R. G.: **Cryogenic Engineering II.** Presented as Paper No. 3 at the AGARD/VKI Lecture Series 111, May 19-23, 1980 at Rhode-Saint-Genese, Belgium and May 27-30, 1980 at NASA Langley Research Center, Hampton, VA.

N81-11051#

Subjects covered in this lecture include: thermal properties of commercial materials; instrumentation, including thermometry, flow, and pressure; and avoidance of two-phase flow.

*The University, Southampton SO9 5NH, Hampshire, U.K.

186 *Wigley, D. A.: **Properties of Materials I.** Presented as Paper No. 4 at the AGARD/VKI Lecture Series No. 111, May 19-23, 1980 at Rhode-Saint-Genese, Belgium and May 27-30, 1980 at NASA Langley Research Center, Hampton, VA.

N81-11052#

Subjects covered in this lecture include: the effect of temperature on the mechanical and physical properties of metals, including strength and toughness; and failure mechanism, influence of cracks and flaws, and fracture toughness.

*The University, Southampton SO9 5NH, Hampshire, U.K.

187 *Hall, Robert M.: **Real-Gas Effects I—Simulation of Ideal Gas Flow by Cryogenic Nitrogen and Other Selected Gases.** Presented as Paper No. 5 at the AGARD/VKI Lecture Series 111, May 19-23, 1980 at Rhode-Saint-Genese, Belgium and May 27-30, 1980 at NASA Langley Research Center, Hampton, VA.

N81-11053#

The thermodynamic properties of nitrogen gas do not thermodynamically approximate an ideal, diatomic gas at cryogenic temperatures. Choice of a suitable equation of state to model its behavior is discussed and the equation of Beattie and Bridgeman is selected as best meeting the needs for cryogenic wind tunnel use. The real-gas behavior of nitrogen gas is compared to an ideal, diatomic gas for the following flow processes: isentropic expansions, normal shocks, boundary layers, and shock wave-boundary layer interactions. The only differences in predicted pressure ratio between nitrogen and an ideal gas that may limit the minimum operating temperatures of transonic cryogenic wind tunnels seem to occur at total pressures approaching 9 atm and total temperatures 10 K below the corresponding saturation temperature, where the differences approach 1 percent for both isentropic expansions and normal shocks. Several alternative cryogenic test gases—air, helium, and hydrogen—are also analyzed. Differences in air from an ideal, diatomic gas are similar in magnitude to those of nitrogen and should present no difficulty. However, differences for helium and hydrogen are over an order of magnitude greater than those for nitrogen or air. It is concluded that helium and hydrogen would not approximate the compressible flow of an ideal, diatomic gas.

*NASA, Langley Research Center, Hampton, VA, 23665

188 *Wigley, D. A.: **Properties of Materials II.** Presented as Paper No. 6 at the AGARD/VKI Lecture Series 111, May 19-23, 1980 at Rhode-Saint-Genese, Belgium and May 27-30, 1980 at NASA Langley Research Center, Hampton, VA.

N81-11054#

Subjects covered in this lecture include: the effect of temperature on the mechanical and physical properties of non-metals, including glasses, polymers, and composites; and sources of information.

*The University, Southampton SO9 5NH, Hampshire, U.K.

189 *Hall, Robert M.: **Real-Gas Effects II — Influence of Condensation on Minimum Operating Temperatures of Cryogenic Wind Tunnels.** Presented as Paper No. 7 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, Va.

N81-11055#

Minimum operating temperatures of cryogenic wind tunnels are limited by real-gas effects. In particular, condensation effects are responsible for the minimum operating temperatures at total pressures up to about 9 atmospheres. The present paper reviews the two primary modes of condensation — homogeneous nucleation and heterogeneous nucleation — and the conditions with which either may limit minimum operating temperatures. Previous hypersonic and supersonic condensation data are reviewed as are data taken in the nitrogen-gas, Langley 0.3-m Transonic Cryogenic Tunnel (TCT). Analysis of data in the 0.3-m TCT suggests that the onset of homogeneous nucleation may be approximated by an analysis by Sivier and that the onset of heterogeneous nucleation is only apparent just below free-stream saturation. Extension of the results from the 0.3-m TCT to other nitrogen-gas cryogenic tunnels is discussed and is shown to depend on length scales, purity of the liquid nitrogen injected for cooling, number of particulates in the flow, and the extent to which the injected liquid nitrogen is evaporated. On the basis of previous data, hybrid air-nitrogen tunnels are expected to realize little, if any, supercooling.

*NASA, Langley Research Center, Hampton, VA, 23665

190 *Scurlock, R. G.: **Cryogenic Engineering III.** Presented as Paper No. 8 at the AGARD/VKI Lecture Series 111, May 19-23, 1980 at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, Va.

N81-11056#

Subjects covered in this lecture include: handling and transfer of liquid nitrogen; cooldown and thermal cycling problems; and safety, including asphyxia, cold burns, explosions, and fire hazards.

*The University, Southampton SO9 5NH, Hampshire, U.K.

191 *Kilgore, Robert A.: **Model Design and Instrumentation Experiences With Continuous-Flow Cryogenic Tunnels.** Presented as Paper No. 9 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980 at NASA Langley Research Center, Hampton, VA.

N81-11057#

The development of wind tunnels that can be operated at cryogenic temperatures has placed several new demands on our ability to build and instrument wind tunnel models. Some of the experiences at the NASA Langley Research Center relative to the design and instrumentation of models for continuous-flow cryogenic wind tunnels are reviewed in this lecture.

*NASA, Langley Research Center, Hampton, VA, 23665

192 *Cadwell, J. D.: **Model Design and Instrumentation for** ...**mittent Tunnels.** Presented as Paper No. 10 at the AGARD/VKI

Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11058#

The concept of a blowdown-to-atmosphere cryogenic wind tunnel was successfully proven when the Douglas Aircraft Company one-foot tunnel first operated cryogenically on May 20, 1977. Since that time a continuing effort has been underway at Douglas to develop the technology required to design, fabricate, and instrument a model that can withstand the hostile environment of a cryogenic flow without sacrificing the acceptable accuracy that can be obtained at conventional temperatures, i.e., 10°C to 65°C. This report summarizes the current state of this technology with a review of the many aspects of the design and instrumentation of a model for a blowdown-to-atmosphere cryogenic wind tunnel. Also included is a discussion of the model-conditioning required before a run in order to minimize the time for the model to stabilize at the adiabatic wall temperature, the model reheat system required after a run when model changes are to be made, and the humidity control of the test section and surrounding area in order to prevent frost from forming on the cold model.

*Douglas Aircraft Co., McDonnell Douglas Corp., 3855 Lakewood Blvd., Long Beach, CA 90846

193 *Kilgore, Robert A.: **Selection and Application of Instrumentation for Calibration and Control of a Continuous-Flow Cryogenic Tunnel.** Presented as Paper No. 11 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, at NASA Langley Research Center, Hampton, VA.

N81-11059#

This lecture describes those aspects of selection and application of calibration and control instrumentation that are influenced by the extremes in the temperature environment to be found in cryogenic tunnels. A description is given of the instrumentation and data acquisition system used in the Langley 0.3-m Transonic Cryogenic Tunnel along with typical calibration data obtained in a 20- by 60-cm two-dimensional test section.

*NASA, Langley Research Center, Hampton, VA, 23665

194 *Cadwell, J. D.: **Calibration of a Blowdown-to-Atmosphere Cryogenic Wind Tunnel.** Presented as Paper No. 12 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11060#

The modification of the existing four-foot trisonic wind tunnel at the Douglas Aircraft Company to a cryogenic facility required considerable change to the existing tunnel internals. When the tunnel comes back on-line early in 1980 a complete tunnel calibration will be made following a shakedown and checkout of the modified facility. The calibration procedure to determine the quality and characteristics of the tunnel airflow of the modified facility at conventional temperatures and at cryogenic temperatures is described. Instrumentation to measure the axial and lateral pressure and temperature variations as a function of Mach number and Reynolds number are reviewed as in the instrumentation to be used in determining the flow angularity and turbulence levels. The variation in tunnel flow parameters that result from the change in displacement thickness due to heat transfer between the warm wall and the cold airflow is also discussed.

*Douglas Aircraft Co., McDonnell Douglas Corp., 3855 Lakewood Blvd., Long Beach, CA 90846

195 *Michel, R.: **The Development of a Cryogenic Wind-Tunnel Driven by Induction.** Presented as Paper No 13 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11061#

This lecture describes flow control and instrumentation studies in a pilot facility (T'2) at ONERA/CERT.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

196 *Kilgore, Robert A.: **Experience in the Control of a Continuous Flow Cryogenic Tunnel.** Presented as Paper No. 14 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11062#

The economical operation of liquid nitrogen cooled cryogenic tunnels is critically dependent on fast and accurate control of the tunnel variables. In this lecture, the control problem of a continuous flow fan driven cryogenic tunnel has been addressed, firstly by developing a lumped multivariable mathematical model of a tunnel and validating the model by reconciling the responses of the Langley 0.3-m Transonic Cryogenic Tunnel to the responses of the mathematical model on a simulator. Finally, the development of laws for the closed loop control of the tunnel pressure and temperature and the successful implementation of a control system for the 0.3-m Transonic Cryogenic Tunnel based on these laws are presented. An accuracy of ±0.25 K in temperature and ±0.017 atm in pressure in the tunnel control has been achieved.

*NASA, Langley Research Center, Hampton, VA, 23665

197 *Cadwell, J. D.: **The Control of Pressure, Temperature and Mach Number in a Blowdown-to-Atmosphere Cryogenic Wind Tunnel.** Presented as Paper No. 15 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11063#

The transonic section of the Douglas Aircraft Company 4-ft blowdown-to-atmosphere wind tunnel was placed in operation in March 1962. The tunnel control system that evolved and was in operation prior to the shutdown for modification is discussed as a starting point since one of the modification objectives is to be able to operate the tunnel in a conventional mode as well as at cryogenic temperatures. The modifications to the basic system to include the control of tunnel total temperature down to 100 K is described. The effects that the injection of large quantities of liquid nitrogen on the pressure control system is shown. The critical timing of the tunnel start considers the opening of the pressure control valve and the initiation of the liquid nitrogen into the airstream which can result in either a varying test section temperature distribution during a blow or reheating the precooled model. The evaluation of a shield to protect the precooled model during the tunnel start when the airstream is changing temperature from warm to the planned operating condition is presented.

*Douglas Aircraft Co., McDonnell Douglas Corp., 3855 Lakewood Blvd., Long Beach, CA 90846

198 *Igoe, William B.: **Characteristics and Status of the U.S. National Transonic Facility.** Presented as Paper No. 17 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11065#

The U.S. National Transonic Facility (NTF), a major application of the cryogenic wind tunnel concept, is under construction at the NASA Langley Research Center and is scheduled to become operational in 1982. It will have a closed return fan-driven circuit with a 2.5-meter square slotted test section, be pressurized up to 8.85 atm, and provide chord Reynolds numbers of 120 million based on a chord of 0.25 m at transonic speeds using cold nitrogen as the test gas. Many of the design features of the NTF, as well as the status of its construction, are presented in this lecture.

*NASA, Langley Research Center, Hampton, VA, 23665

199 *Cadwell, J. D.: **Progress Report on the Douglas Aircraft Company Four-Foot Cryogenic Wind Tunnel.** Presented as Paper No. 18 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11066#

The McDonnell Douglas Corporation approved the modification of the existing Douglas Aircraft Company 4-ft. trisonic wind tunnel to a cryogenic facility in mid 1976. The successful operation of the one-foot pilot tunnel in May 1977 gave the final technical approval to proceed with the four-foot tunnel modification program. This lecture gives an update on the progress of the modification. In addition, a review of the test technique development program that will provide the technology necessary to conduct the production type testing required for the design of new or derivative type aircraft programs is presented.

*Douglas Aircraft Co., McDonnell Douglas Corp., 3855 Lakewood Blvd., Long Beach, CA 90846

200 *Michel, R.: **A Cryogenic Transonic Intermittent Tunnel Project: The Induced-Flow Cryogenic Wind-Tunnel T2 at ONERA/CERT.** Presented as Paper No. 19 at the AGARD/VKI Lecture Series 111, May 19-23, 1980 at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11067#

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

201 *Hartzuiker, J. P.; and *North, R. J.: **The European Transonic Wind Tunnel, ETW.** Presented as Paper No. 16 at the AGARD/VKI Lecture Series 111, May 19-23, 1980, at Rhode-Saint-Genese, Belgium, and May 27-30, 1980, at NASA Langley Research Center, Hampton, VA.

N81-11064#

This lecture summarizes the present situation concerning ETW: Aerodynamics, performance, design, model handling, nitrogen systems, controls, etc. ... A short descripton is presented of the pilot tunnel, PETW, which is now under construction. Finally, the program on model design and instrumentation is described. Attention is paid especially to the cryogenic aspects of ETW.

*Technical Group, ETW, National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

202 *Tobler, R. L.: **Materials for Cryogenic Wind Tunnel Testing.** NASA CR-164556, Rept. No. NBSIR 79-1624, May 1980, 135 pp.

N81-27120#

A study was conducted to guide the evaluation and selection of materials and techniques to be used in construction of model aircraft for cryogenic wind tunnel testing. In this report, the mechanical, thermal, and electrical property behavior of materials at temperatures as low as 77 K is briefly reviewed. Metals, structural alloys, non-metals, composites, joining methods, coatings, sealants, adhesives, contact agents, lubricants, transducers, and instrumentation for cryogenic applications are discussed. Acceptable structural materials, conductors, and insulators are discussed for service at temperatures in the range 367 to 77 K. Numerous references to handbooks and other cryogenic data sources are cited as a guide to additional information.

*National Bureau of Standards, Boulder, CO, 80302

Contract NASA Order L-59674-A

203 *Wegener, Peter P.: **Study of Experiments on Condensation of Nitrogen by Homogeneous Nucleation at States Modelling Those on the National Transonic Facility. Final Report.** NASA CR-163217, May 1980, 58 pp.

N80-25294#

A cryogenic wind tunnel is based on the twofold idea of lowering drive power and increasing Reynolds number by operating with nitrogen near its boiling point. There are two possible types of condensation problems involved in this mode of wind tunnel operation. They concern the expansion from the nozzle supply to the test section at relatively low cooling rates, and secondly the expansion around models in the test section. This secondary expansion involves higher cooling rates and shorter time scales. In addition to these two condensation problems it is not certain what purity of nitrogen can be achieved in a large facility. Therefore, one cannot rule out condensation processes other than these of homogeneous nucleation.

*Yale University, Dept. of Engineering and Science, 206 Elm Ave., New Haven, CT, 06520

NASA Grant NSG-1612

204 *Ladson, Charles L.; and *Kilgore, Robert A.: **Instrumentation for Calibration and Control of a Continuous-Flow Cryogenic Tunnel.** NASA TM-81825, May 1980, 11 pp. This paper is based on one presented at the AGARD/VKI Lecture Series 111 on Cryogenic Wind Tunnels, May 1980.

N80-24265#

This paper describes those aspects of selection and application of calibration and control instrumentation that are influenced by the extremes in the temperature environment to be found in cryogenic tunnels. A description is given of the instrumentation and data acquisition system used in the Langley 0.3-m Transonic Cryogenic Tunnel along with typical calibration data obtained in a 20- by 60-cm two-dimensional test section.

*NASA, Langley Research Center, Hampton, VA, 23665

205 *Ferris, Alice T.: **Force Instrumentation for Cryogenic Wind Tunnels Using One-Piece Strain-Gage Balances.** NASA TM-81845, June 1980, 17pp. (This paper is based on one presented at the NASA Cryogenic Technology Conference held at NASA Langley Research Center, Nov. 27-29, 1979.)

N81-17406#

The use of cryogenic temperatures in wind tunnels to achieve high Reynolds numbers has imposed a harsh operating environment on the force balance. Laboratory tests were conducted to study the effect cryogenic temperatures have on balance materials, gages, wiring, solder, adhesives and moisture proofing. Wind tunnel tests were conducted using a one-piece three-component balance to verify laboratory results. These initial studies indicated that satisfactory force data can be obtained under steady state conditions.

*NASA, Langley Research Center, Hampton, VA, 23665

206 *Balakrishna, S. **Minimum Energy Test Direction Design in the Control of Cryogenic Wind Tunnels.** Progress Rept. period ending June 1980. NASA CR-163244, June 1980. 56 pp.

N81-11457#

This report details the test direction planning problems associated with cryogenic wind tunnels, analyzed as a part of the project "Modeling and Control of Transonic Cryogenic Tunnels," sponsored by NASA/Langley Research Center. The report is concerned with realizing desired flow Reynolds number-Mach number combinations at which data is sought, with minimum liquid nitrogen consumption. The contents of this document complement the reports on modeling phase activity in entry 167 and the control analysis phase activity in entry 179 of this bibliography.

*Old Dominion University, Norfolk, VA. 23508

NASA Grant NSG-1503

207 *Hanson, Perry W. **An Assessment of the Future Roles of the National Transonic Facility and the Langley Transonic Dynamics Tunnel in Aeroelastic and Unsteady Aerodynamic Testing.** NASA TM-81839, June 1980. 52 pp.

N80-28377#

The characteristics and capabilities of the two tunnels that relate to studies in the fields of aeroelasticity and unsteady aerodynamics are discussed. Scaling considerations for aeroelasticity and unsteady aerodynamics testing in the two facilities are reviewed, and some of the special features (or lack thereof) of the Langley Research Center Transonic Dynamics Tunnel (TDT) and the National Transonic Facility (NTF) that will weigh heavily in any decisions of conducting a given study in the two tunnels are discussed. For illustrative purposes a fighter and a transport airplane are scaled for tests in the NTF and in the TDT, and the resulting model characteristics are compared. The NTF was designed specifically to meet the need for higher Reynolds number capability for flow simulation in aerodynamic performance testing of aircraft designs. However, the NTF can be a valuable tool for evaluating the severity of Reynolds number effects in the areas of dynamic aeroelasticity and unsteady aerodynamics. On the other hand, the TDT was constructed specifically for studies and tests in the field of aeroelasticity. Except for tests requiring the Reynolds number capability of the NTF, the TDT will remain the primary facility for tests of dynamic aeroelasticity and unsteady aerodynamics.

*NASA, Langley Research Center, Hampton, VA. 23665

208 *Bursik, Joseph W.; and **Hall, Robert M. **Effects of Various Assumptions on the Calculated Liquid Fraction in Isentropic Saturated Equilibrium Expansions.** NASA TP-1682, June 1980. 33 pp.

N80-25615#

The saturated equilibrium expansion approximation for two-phase flow often involves ideal-gas and latent-heat assumptions to simplify the solution procedure. This approach is well documented by Wegener and Mack and works best at low pressures where deviations from ideal-gas behavior are small. A thermodynamic expression for liquid mass fraction that is decoupled from the equations of fluid mechanics is used in this paper to compare the effects of the various assumptions on nitrogen-gas saturated equilibrium expansion flow starting at 8.81 atm, 2.99 atm, and 0.45 atm, which are conditions representative of transonic cryogenic wind tunnels. For the highest-pressure case, the entire set of ideal-gas and latent-heat assumptions are shown to be in error by 62 percent for the value of heat capacity and latent heat used in this paper. An approximation of the exact, real-gas expression is also developed using a constant, two-phase isentropic expansion coefficient which results in an error of only 2 percent for the high-pressure case.

*Rensselaer Polytechnic Inst., Troy, NY 12181

**NASA, Langley Research Center, Hampton, VA. 23665

209 *Fancher, M. F. **Hot-film Anemometry for Boundary Layer Transition Detection in Cryogenic Tunnel.** European Mechanical Colloquium, Euromech 132, held at the Ecole Centrale de Lyon, Rhone, France, July 2-4, 1980. 16 pp.

CN-153,419

Detailed information on the boundary-layer transition and separation is given. About 100 sensors were located on an aerofoil by means of a thin plastic film (Kapton or Mylar). Experiments were run in a cryogenic tunnel. The important question of the heat loss to the substrate did not seem, however, to have been examined. For this particular problem, a useful reference is Brison, Charnay & Comte-Bellot (1979).

*Douglas Aircraft Co., McDonnell Douglas Corp., 3855 Lakewood Blvd., Long Beach, CA 90846

NOTE: This paper does not appear in Euromech 132, even though it was presented. Contact author for copies.

210 *Dueker, M.; and *Koppenwallner, G. **Comparisons Between Experimental Observations and Predictions Obtained With Classical Homogeneous Nucleation Theory for Nitrogen Condensation in Large Freejet Experiments.** Presented as Paper No. 172 at the 12th International Symposium on Rarefied Gas Dynamics, Charlottesville, VA., July 7-12, 1980. In vol. 74, "Progress in Astronautics and Aeronautics," pp. 1190-1210.

A82-13072#

Classical condensation theory is tested for its ability to predict condensation onset and the ensuing droplet growth process in freejet expansions of nitrogen. A computer program combining nucleation theory, a droplet growth model, and the gas dynamics of freejet flow is used for this purpose. Comparisons of the theoretical results with experiments, covering a large range of expansion isentropes, reveal generally unsatisfactory results. Of various correction schemes tested, a particular surface tension assumption for the solid clusters gave at least approximate agreement with measured data.

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211 *Johnson, Charles B. **Theoretical Study of Nonadiabatic Boundary-Layer Stabilization Times in a Cryogenic Wind Tunnel for Typical Stainless Steel Wing and Fuselage Models.** NASA TM-80212, July 1980. 43 pp.

N80-25614#

The time varying effect of nonadiabatic wall conditions on boundary layer properties was studied for a two-dimensional wing section and an axisymmetric fuselage. The wing and fuselage sections are representative of the wing root chord and fuselage of a typical transport model for the National Transonic Facility. The analysis was made with a solid wing and three fuselage configurations (one solid and two hollow with varying skin thicknesses) all made from AISI type 301S stainless steel. The displacement thickness and local skin friction were investigated at a station on the model in terms of the time required for these two boundary layer properties to reach an adiabatic wall condition after a 50 K step change in total temperature. The analysis was made for a free stream Mach number of

0.85, a total temperature of 117 K, and stagnation pressures of 2, 6, and 9 atm

*NASA, Langley Research Center, Hampton, VA, 23665

212 *Mohan, S. R., and *Stollery, J. L.: **A Study of the Temperatures Achievable by Expansion of High Pressure Gas.** The Aeronautical Journal, vol. 84, Aug. 1980, pp. 253-255.

A81-27896

An experimental investigation of the achievement of cryogenic temperatures by the adiabatic isentropic expansion of a gas is presented. The test apparatus is a light piston tunnel, and the working gas nitrogen. It was determined that cryogenic temperatures were achieved by a polytropic process with an exponent of between 1.3 and 1.4. To achieve a temperature of 120 K from an initial temperature of 300 K, a pressure ratio of 35 will typically be required.

*Cranfield Institute of Technology, Cranfield Bedford MK 43 0AL, U.K.

213 *Balakrishna, S.: **Effects of Boundary-Layer Treatment on Cryogenic Wind-Tunnel Controls.** Progress Rept, period ending Aug. 1980, NASA CR-159372, Aug. 1980, 62 pp.

N81-12120#

This report analyzes the manner in which various possible schemes for sidewall boundary-layer treatment, that can be used to achieve a two-dimensional flow field around the model in the Langley 0.3-m Transonic Cryogenic Tunnel, affect the basic tunnel controls. This work constitutes a part of the project "Modeling and Control of Transonic Cryogenic Tunnels" sponsored by NASA Langley Research Center. The contents of this document complement other reports of the project.

*Old Dominion University, Norfolk, VA, 23508

NASA Grant NSG-1503

214 *Thibodeaux, Jerry J., and **Balakrishna, S.: **Development and Validation of a Hybrid-Computer Simulator for a Transonic Cryogenic Wind Tunnel.** NASA TP-1695, Sept. 1980, 84 pp.

N80-31413#

A study has been undertaken to model the cryogenic-wind-tunnel process, to validate the model by the use of experimental data from the Langley 0.3-m Transonic Cryogenic Tunnel, and to construct an interactive simulator of the cryogenic tunnel using the validated model. Additionally, this model has been used for designing closed-loop feedback control laws for regulation of temperature and pressure in the 0.3-m cryogenic tunnel. The global mathematical model of the cryogenic tunnel that has been developed consists of coupled, nonlinear differential governing equations based on an energy-state concept of the physical cryogenic phenomena. Process equations and comparisons between actual tunnel responses and computer-simulation predictions are given. Also included are the control laws and simulator responses obtained by using the feedback schemes for closed-loop control of temperature and pressure.

*NASA, Langley Research Center, Hampton, VA, 23665

**Old Dominion University, Norfolk, VA, 23508

215 *Gloss, Blair B.: **Some Aerodynamic Considerations Related to Wind Tunnel Model Surface Definition.** NASA TM-81820, Sept. 1980, 13 pp.

N80-32376#

The aerodynamic considerations related to model surface definition are examined with particular emphasis in areas of fabrication tolerances, model surface finish, and orifice induced pressure errors. The effect of model surface roughness texture on skin friction is also discussed.

*NASA, Langley Research Center, Hampton, VA, 23665

216 *Buckley, J. D., and *Sandefur, P. G., Jr.: **Low-Temperature Solder for Joining Large Cryogenic Structures.** NASA TM-81836, Sept. 1980, 15 pp.

N80-32490#

Three joining methods were considered for use in fabricating cooling coils for the National Transonic Facility. After analysis and preliminary testing, soldering was chosen as the cooling coil joining technique over mechanical force fit and brazing techniques. Charpy V-Notch tests, cyclic thermal tests (ambient to 77.8 K) and tensile tests at cryogenic temperatures were performed on solder joints to evaluate their structural integrity. It was determined that low temperature solder can be used to ensure good fin-to-tube contact for cooling-coil applications.

*NASA, Langley Research Center, Hampton, VA, 23665

217 *Maurer, F.: **Project European Transonic Windtunnel. (Projekt Europaischer Transschall-Windkanal).** Bundesministerium fur Forschung und Technologie, Statusseminar zur Luftfahrtforschung und Luftfahrt-technologie, 2nd, Garmisch Partenkirchen, West Germany, Oct. 8-9, 1980, Paper. 38 pp. (In German.)

A81-37640#

A status report concerning the project 'European Transonic Windtunnel' is provided. The report describes the situation existing after the predesign phase and refers to the problem of the new discussion regarding the test section cross section with respect to size and form. The organization of the project definition phase is based on a memorandum of understanding between West Germany, France, Great Britain, and Holland. The project had been initiated because it was felt that there was an urgent requirement for a high-Reynolds-number transonic wind tunnel in Europe. The requirement is to be satisfied by means of a pressurized continuous-flow tunnel using nitrogen as the test gas, and capable of being operated over a range of temperatures from ambient down to about 90 K.

*Institute for Experimental Fluid Mechanics, DFVLR, Goettingen and Cologne-Porz, West Germany (FRG)

218 *Howell, R. R.; and *Joplin, S. D.: **A System for Model Access in Tunnels With an Unbreathable Test Medium.** International Council of the Aeronautical Sciences, Proceedings, 12th Congress, Munich, West Germany, Oct. 12-17, 1980, pp. 817-822

A81-11601 (pp. 817-822)
A81-11672

In many specialty wind tunnels, test gases other than ambient air are used to meet special testing requirements. A typical example is the use of freon as the test gas to achieve a realistic density ratio between gas and model for exploring flutter stability boundaries. Another example is the use of pressurized air to elevate the stream density and enhance Reynolds number or dynamic pressure simulation. Such specialty tunnels require a system of access to the model which will allow services and changes to the model without exposing personnel to the unnatural and perhaps hostile environment or requiring the venting and purging of the entire tunnel circuit. This paper will describe the plenum and model access systems for the forthcoming U.S. National Transonic Facility where gaseous nitrogen at temperatures between 338 and 78 K and at pressures to 9 bars is used as the test medium. The operation at cold temperatures imposes some additional requirements which make the access sys-

tems more difficult to design and time consuming to operate than for conventional (ambient temperature) wind tunnels.

*NASA, Langley Research Center, Hampton, VA, 23665

219 *Balakrishna, S. **Modeling and Control of Transonic Cryogenic Wind Tunnels.** Final Summary Report, Period ending Oct. 1980. NASA CR-163588, Oct. 1980. 53 pp.

N80-32403#

This report summarizes the many faceted research activities of the project "Modeling and Control of Transonic Cryogenic Wind Tunnels," which was sponsored by the NASA Langley Research Center. Reported are the model synthesis activity, control analysis activity, test direction design analysis, and effects of boundary-layer treatment on cryotunnel controls. The activities in each of these areas are briefly reviewed, and they are complemented by recommendations for improving some of the engineering systems of the 0.3-m Transonic Cryogenic Tunnel (TCT) to which the bulk of the research was oriented.

*Old Dominion University, Norfolk, VA, 23508
NASA Grant NSG-1503

220 *Lawing, Pierce L., *Sandefur, Paul G., Jr., and *Wood, William H. **A Construction Technique for Wind-Tunnel Models.** NASA Tech. Brief LAR-12710, Fall 1980.

Miniature wind-tunnel models must satisfy stringent physical requirements, including high strength, good surface finish, and corrosion resistance. Some of the most troublesome problems result from the internal steel tubes that lead to small, pressure-sensing, surface orifices. These tubes may plug or leak, and the cavities they require weaken the model. Since the plumbing cannot be installed until late in the machining process, considerable fabrication time is wasted if defects arise at that point. These problems are overcome by machining the pressure channels as an integral part of the model. A method of accomplishing this is described. In addition to solving construction problems for wind-tunnel models, this technique should be useful in fuel injection, transpiration cooling, and similar applications involving small elements of fluid flow. Since the technique has been developed for 17-4 PH alloy stainless steel, it can be used for corrosive or high-temperature environments.

*NASA, Langley Research Center, Hampton, VA, 23665

For further information, contact the Technology Utilization Officer, M.S. 139, at Langley Research Center and refer to LAR-12710.

221 *Blanchard, A., *Dor, J. B., *Mignosi, A.; and *Breil, J. F.. **Research on a Cryogenic Wind Tunnel Operating by Induction.** (Recherches sur une Soufflerie Cryogenique Fonctionnant par Induction). Paper AAAF NT 80-32 at 17th AAAF Colloque d'Aerodynamique Appliquee, Grenoble, France, Nov. 12-14, 1980. 42 pp. (In French.) (For the English translation see the following entry in this compilation.)

A81-33935#

The paper presents circuit design and operation of the ONERA pilot T'2 low temperature wind tunnel, a technology developed at ¼ scale for transfer to the T2 European Transonic Wind Tunnel. The studies focus especially on the choice of internal insulation and the liquid nitrogen injection system. High Reynolds numbers obtained allow close in-flight simulation using cryogenic gusts. Initial tests comprised temperature distributions, thermal and pressure fluctuations, pulverization of liquid nitrogen droplets by low speed injection, and control and efficiency checks on the use of cryogenic liquids, including protection of personnel from leakage through microcracks, accomplished by use of a Kevlar reinforced glass lining of the concave inner surface of the vessel.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

222 *Blanchard, A., *Dor, J. B., *Mignosi, A., and *Breil, J. F. **Research on an Induction Driven Cryogenic Wind Tunnel.** In La Recherche Aerospatiale, Bi-Monthly Bulletin no. 1981-2, Mar.-Apr. 1981. Translation into English. ESA-TT-713, Sept. 1981, pp. 63-77.

A81-43393#(Translation)
N82-14394#(Translation)

The cryogenitization of an induction driven transonic wind tunnel is discussed. Internal insulation and the design of a liquid nitrogen injection system are considered. A unit of 32 injectors is arranged at the periphery of the first diffuser in two rows. Each injector is controlled by a solenoid valve. Several elements can be brought together at the control point to form a 10 bit digital regulation unit. The nitrogen pulses are kept symmetrical by varying the response time of the solenoid valves. This induction system works well since the increase in nozzle performance compensates increase of flow in the test section due to the drop in temperature. It should be suitable with nitrogen gas. Composite and homogeneous insulating materials were repeatedly plunged into liquid nitrogen. All reveal defects when exposed to stress induced by differences in the expansion between their internal and external faces. Internal surfaces must be reinforced with polyurethane.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

223 *Mignosi, A., *Faulmann, D., and *Seraudie, A. **Induction Driven Transonic Wind Tunnel T-2: Operation at Room Temperature and Cryogenic Adaptation.** Association Aeronautique et Astronautique de France, 17th, Colloque d'Aerodynamique Appliquee, Grenoble, France, Nov. 12-14, 1980. Rept. ONERA-TP-1980-142, 1980. 36 pp. (In French.) Translation into English of La Recherche Aerospatiale, Bulletin Bimestriel no. 1981-3, May-June 1981, pp. 203-215. Rept. no. ESA-TT-714, pp. 63-74.

A81-21916#(In French)
N82-19158#(In English)

The transformation of the induction driven wind tunnel T2 (0.4 m×0.4 m) into a cryogenic intermittent wind tunnel which uses high pressure air as driving gas and nitrogen as coolant is described. The operating mode and optimization of the wind tunnel for low temperature operation are discussed. Theoretical and experimental aspects of the transformed facilities, i.e., modification of the circuit, thermal insulation techniques, liquid nitrogen injection, start up process, cryogenic operating mode, and expected performance are presented.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

224 *Maurer, F., *Viehweger, G., and *Lorenz-Meyer, W. **Developments in the Area of Cryo-Wind Tunnel Technology by the DFVLR** (Deutsche Forschungs- und Versuch-sanstalt fuer Luft-und Raumfahrt). DFVLR-Nachrichten, Nov. 1980, pp. 8-12. (In German.) For English translation see the following entry in this compilation.

A81-15702

Research is described of new wind tunnel assemblies which, in contrast to present facilities, simulate free flight conditions. In addition to Mach number, the Reynolds number is taken into consideration for similitude of friction level and flow separation. The German-Dutch subsonic wind tunnel (DNW) approaches the desired results, though the drive power increases not only with the second power of the size but increases with the third power of the speed.

*DFVLR Porz-Wahn, Postfach 90 60 58, 5000 Cologne 90, West Germany (FRG)

225 *Maurer, Franz, *Viehweger, Guenther, and *Lorenz-Meyer, Wolfgang. **Development in the Area of Cyro-Wind Tunnel Technology.** NASA-TM 75475, April 1981. 16 pp. Translation of "Arbeiten der DFVLR auf dem Gebiet der Kryo-Windkanaltechnik" DFVLR-Nachrichten, no. 31, Nov. 1980, pp. 8-12. (For original German and abstract see the preceding entry in this compilation.) Available to U.S. Gov't. Agencies and their Contractors Only.

X81-10220

Transl. by Scientific Translation Service, Santa Barbara, CA.

*DFVLR Porz-Wahn, Postfach 90 60 58, 5000 Cologne 90, West Germany (FRG)

NASA Contract NASw-3198

226 *Lawing, Pierce L., *Adcock, Jerry B., and *Ladson, Charles L. **A Fan Pressure Ratio Correlation in Terms of Mach Number and Reynolds Number for the Langley 0.3-Meter Transonic Cryogenic Tunnel.** NASA TP 1752, Nov. 1980. 18 pp.

N81-100005#

Calibration data for the two-dimensional test section of the Langley 0.3-Meter Transonic Cryogenic Tunnel are used to develop a Mach number Reynolds number correlation for the fan pressure ratio in terms of test section conditions. It is shown that well-established engineering relationships can be combined to form an equation which is functionally analogous to the correlation. Additionally, a geometric loss coefficient which is independent of Reynolds number or Mach number can be determined. Present and anticipated uses of this concept include improvement of tunnel control schemes, comparison of efficiencies for operationally similar wind tunnels, prediction of tunnel test conditions and associated energy usage, and determination of Reynolds number scaling laws for similar fluid flow systems.

*NASA Langley Research Center, Hampton, VA, 23665

227 *McKinney, L. Wayne and **Baals, Donald D., editors. **High Reynolds Number Research — 1980.** NASA CP-2183, Sept. 1981. 325 pp.

N81-31130#

This is a compilation of papers presented at the Workshop on High Reynolds Number Research held December 9-11, 1980, at the Langley Research Center. It also includes panel recommendations for research programs for the National Transonic Facility in the following areas:

- Fluid dynamics
- High lift
- Configuration aerodynamics
- Aeroelasticity and unsteady aerodynamics
- Wind-tunnel/flight correlation
- Space vehicles
- Theoretical aerodynamics

(A Workshop on High Reynolds Number Research was also held in 1976 and is reported in NASA CP-2009 (N77-27139), for which see #48 through #51 in this compilation.)

*NASA Langley Research Center, Hampton, VA, 23665

**Joint Institute for Advancement of Flight Sciences, The George Washington University, NASA, Langley Research Center, Hampton, VA 23665

228 *Young, Clarence P., Jr. **Pathfinder Model Program for the National Transonic Facility.** High Reynolds Number Research-1980, paper no. 5, NASA CP-2183 (N81-31130), pp. 37-52. (Comments on pp. 291-292.) (Presented Dec. 1980.)

N81-31135#

An overview of the Pathfinder Models Program is presented in this paper. The Pathfinder program is a major research and development activity that is underway in support of the National Transonic Facility Activation Plan. The program scope, models design approach, and Pathfinder model configurations are presented along with a discussion of major supportive program activities. In addition, the anticipated design criteria for NTF models are presented.

*NASA, Langley Research Center, Hampton, VA, 23665

229 *Lawing, Pierce L., and *Kilgore, Robert A. **Model Experience in the Langley 0.3-m Transonic Cryogenic Tunnel.** High Reynolds Number Research — 1980, paper no. 6, NASA CP-2183 (N81-31130), pp. 53-74. (Comments on p. 293.) (Presented Dec. 1980.)

N81-31136#

The development of wind tunnels that can be operated at cryogenic temperatures has placed several new demands on our ability to build and instrument wind-tunnel models. This paper presents a brief summary of the model building, development, and testing experience gained during 8 years of operation of the Langley 0.3-m Transonic Cryogenic Tunnel.

*NASA, Langley Research Center, Hampton, VA, 23665

230 *Guarino, Joseph F.: **Instrumentation Systems for the National Transonic Facility.** High Reynolds Number Research — 1980, paper no. 7, NASA CP-2183 (N81-31130), pp. 75-80. (Comments on p. 294.) (Presented Dec. 1980.)

N81-31137#

Instrumentation and measurement systems are important elements in any complex research facility. The National Transonic Tunnel with its unique operational characteristics is clearly a complex facility and as such represents a significant challenge to wind tunnel instrument designers. This paper briefly describes the instrument requirements imposed by the new testing environment, the instrument systems being provided for facility calibration and operation, and the research and development activities directed at meeting overall instrument and measurement requirements.

*NASA, Langley Research Center, Hampton, VA, 23665

231 *Ladson, Charles L., and *Kilgore, Robert A.: **Instrumentation for Calibration and Control of a Continuous-Flow Cryogenic Tunnel.** High Reynolds Number Research — 1980, paper no. 8, NASA CP-2183 (N81-31130), pp. 81-92. (Comments on p. 295.) (Presented Dec. 1980.)

N81-31138#

This paper describes those aspects of selection and application of calibration and control instrumentation that are influenced by the extremes in the temperature environment to be found in cryogenic tunnels. A description is given of the instrumentation and data acquisition system used in the Langley 0.3-m Transonic Cryogenic Tunnel along with typical calibration data obtained in a 20- by 60-cm two-dimensional test section.

*NASA, Langley Research Center, Hampton, VA, 23665

232 *Hall, Robert M.: **Onset of Condensation Effects in Cryogenic Wind Tunnels.** High Reynolds Number Research — 1980, paper no. 9, NASA CP-2183 (N81-31130), Sept. 1981, pp. 93-104. (Comments on pp. 295-296.) (Presented Dec. 1980.)

N81-31139#

The onset of condensation effects in cryogenic wind tunnels limits their minimum operating temperatures. If this onset of effects occurs below saturation temperature, then the tunnels may be operated at the lower temperatures and additional benefits to cryogenic tunnel operation, such as increased Reynolds number capability and reduced operating costs, will result. Both homogeneous and heterogeneous nucleation processes are discussed as they pertain to continuous-flow cryogenic wind tunnels. Examples from condensation experiments in the Langley 0.3-meter Transonic Cryogenic Tunnel are also reviewed.

*NASA, Langley Research Center, Hampton, VA, 23665

233 *Stainback, P. Calvin; and *Fuller, Dennis E.: **Flow Quality Measurements in Transonic Wind Tunnels and Planned Calibration of the National Transonic Facility.** High Reynolds Number Research – 1980, paper no. 10, NASA CP-2183, (N81-31130), Sept. 1981, pp. 105-122 (Comments on pp. 297-300.) (Presented Dec. 1980.)

N81-31140#

The need for mean flow and dynamic flow quality measurements was considered for the National Transonic Facility (NTF). Past experience in making flow quality measurements in transonic flows and at cryogenic temperatures was used to guide the selection of methods to be used in the NTF. It appears that suitable instrumentation will be available and adequate experience has been obtained to insure that the proper calibration of the NTF can be made.

*NASA, Langley Research Center, Hampton, VA, 23665

234 *Kempka, S. N.; and *Clausing, A. M.: **The Influences of Variable Properties on Natural Convection From Vertical Surfaces.** University of Illinois Technical Rept. ME-TN-81-9180-2, Vol. II of Final Rept., Jan. 1981. 59 pp.

N82-77735

A central receiver atop a tower absorbs solar energy reflected to it from a surrounding array of heliostats. The thermal losses from the receiver are an unknown factor. Fundamental research in convective heat transfer is required to obtain data necessary for accurate prediction of thermal losses. One method of obtaining combined convection data is cryogenic modeling. Low temperature experiments performed in the UIUC Cryogenic Heat Transfer Facility have been shown to agree well with existing correlations. A description of the apparatus is given.

*University of Illinois at Urbana-Champaign, Urbana, IL, 61801
Basic Research Sponsored by Sandia Nat. Labs.

Research Grant No. 87-9180

235 *Ferris, Alice T.; and *Moore, Thomas C.: **Force Instrumentation for Cryogenic Wind Tunnels.** Presented at the 27th International Instrumentation Symposium, Indianapolis, Indiana, April 27-30, 1981, pp. 149-160.

A82-41783

One-piece multicomponent strain-gage force transducers have been utilized successfully to measure aerodynamic loads in wind tunnel models for many years. These transducers are designed to, and have historically, operated in temperatures ranging from 295 K to 355 K. A new wind tunnel now under construction at Langley Research Center in Hampton, Virginia, will obtain more accurate data in aircraft research by simulating full scale Reynolds numbers. This facility will have the capability of wind-tunnel model testing at cryogenic temperatures (down to 77 K) and high pressure (up to 9 atm). An extensive testing program, including cryogenic wind tunnel tests, has determined materials and techniques that are usable to obtain accurate force measurements at these very low temperatures. The effect of the cryogenic environment on the transducer material and on the transducer's electrical components (including strain gages, wiring, solder, and moistureproofing), the gaging techniques developed to eliminate undesirable effects, and the results of wind tunnel verification tests are presented.

*NASA, Langley Research Center, Hampton, VA, 23665

236 *Gartrell, Luther R.; *Gooderum, Paul B.; *Hunter, William W., Jr.; and *Meyers, James F.: **Laser Velocimetry Technique Applied to the Langley 0.3-Meter Transonic Cryogenic Tunnel.** NASA TM-81913, Apr. 1981. 35 pp.

N81-22331#

A low-power (15 mW) laser velocimeter operating in the forward-scatter mode has been used to measure free-stream mean velocities in the Langley 0.3-m Transonic Cryogenic Tunnel. Velocity ranging from 51 to 235 m/s was measured with at least ±1-percent accuracy. These measurements were obtained for a variety of nominal tunnel conditions: Mach numbers from 0.20 to 0.77, total temperatures from 100 to 250 K, and pressures from 101 to 152 kPa (1.0 to 1.5 atm). Particles were not injected to augment the existing Mie scattering material. It is postulated that the existing light scattering material in these tests was liquid nitrogen droplets normally injected to control the tunnel temperature. Signal levels obtained during the tests indicated that the average particulate diameter was greater than 1.0 μm. Tunnel vibrations and thermal effects, which were considered to be potential problems before the tests, had no detrimental effects on the optical system.

*NASA, Langley Research Center, Hampton, VA, 23665

237 *Schroeder, W.: **European Transonic Wind Tunnel ETW —Status of the Project at the End of the Predesign Phase.** DGLR Paper 81-027. Presented at Aachen, West Germany, May 11-14, 1981. 27 pp. (In German.)

A81-47563#

The predesign of the basic ETW with a test cross-section area of 3.2 m^2 and a maximum pressure of 4.5 bar was completed in spring 1980. The need for a European transonic wind tunnel for conducting tests at high Reynolds numbers is discussed, taking into account current wind-tunnel developments in Europe and the U.S. The specifications for the ETW are considered. The maximum Reynolds number for the ETW has been raised to a value of 50 million. This was done to enhance the cost effectiveness of testing in the ETW and to reduce development risks. The ETW will, therefore, provide for future European aircraft development conditions for full-scale testing over a wide flight range. Attention is given to the performance spectrum of the ETW, an evaluation of the predesign, operational aspects of the ETW, the thermal inertia of the model, the pilot wind tunnel, the cryogenic technology program, and the future phases of the ETW program.

*DGLR, Aachen, West Germany (FRG)

238 *Johnson, Charles B.; and *Adock, Jerry B.: **Measurement of Recovery Temperature on an Airfoil in the Langley 0.3-m Transonic Cryogenic Tunnel.** Presented at the AIAA 16th Thermophysics Conference, Palo Alto, Calif., June 23-25, 1981.

AIAA-81-1062 A81-39074#

Experimental measurements of recovery temperature were made on an airfoil in the Langley 0.3-m Transonic Cryogenic Tunnel at Mach numbers of 0.60 and 0.84 over a Reynolds number per meter range from about 15×10^6 to about 335×10^6. The measured recovery temperatures were considerably below those associated with ideal-gas ambient temperature wind tunnels. This difference was accen-

tuated as the stagnation pressure increased and the total temperature decreased. A boundary-layer code modified for use with cryogenic nitrogen adequately predicted the measured adiabatic wall temperature at all conditions. A quantitative on-line assessment of the nonadiabatic condition of a model can be made during the operation of a cryogenic wind tunnel by using a correlation for the adiabatic wall temperature which is only a function of total temperature, total pressure, and local Mach number on the model.

*NASA, Langley Research Center, Hampton, VA, 23665

239 *Wigley, D. A. **The Structure and Properties of Diffusion Assisted Bonded Joints in 17-4 PH, Type 347, 15-5 PH and Nitronic 40 Stainless Steels.** NASA CR-165745, July 1981. 30 pp.

N81-30251#

Initial trials carried out at NASA Langley Research Center have demonstrated that diffusion assisted bonds can be formed in 17-4 PH, 15-5 PH, type 347 and Nitronic 40 stainless steels using electrodeposited copper as the bonding agent. The bonds are analyzed by conventional metallographic, electron microprobe analysis, and scanning electron microscopic techniques as well as Charpy V-Notch impact tests at temperatures of 77 and 300 K. The results are discussed in terms of a postulated model for the bonding process.

*The University, Southampton SO9 5NH, Hampshire, U.K.

Contract NAS1-16000 (Research supported by Kentron International, Inc., Univ. of Southampton, and NASA).

240 *Boyden, Richmond P., and *Johnson, William G., Jr.: **Preliminary Results of Buffet Tests in a Cryogenic Wind Tunnel.** NASA TM-81923, July 1981. 37 pp.

N81-31124#

Buffet tests of two wings with different leading-edge sweep have shown that it is feasible to use the standard wing root bending moment technique in a cryogenic wind tunnel. The results for the 65° sweep delta wing indicate the importance of matching the reduced frequency parameter in model tests for planforms which are sensitive to reduced frequency parameter if quantitative buffet measurements are required. The unique ability of a pressurized cryogenic wind tunnel to separate the effects of Reynolds number and of aeroelastic distortion by variations in the tunnel stagnation temperature and pressure was demonstrated.

*NASA, Langley Research Center, Hampton, VA, 23665

241 *Fuller, D. E.: **Guide for Users of the National Transonic Facility.** NASA TM-83124, July 1981. 41 pp.

N81-29139#

The National Transonic Facility (NTF) is a fan-driven, closed-circuit, continuous-flow, pressurized wind tunnel. The test section is 2.5 m×2.5 m and 7.62 m long with a slotted-wall configuration. The NTF will have a Mach number range from 0.2 to 1.2, with Reynolds numbers up to 120×10^6 at Mach 1 (based on a reference length of 0.25 m). The pressure range for the facility will be from 1 to about 9 bars (1 bar=100 kPa), and the temperature can be varied from 340 to 78 K. This report provides potential users of the NTF with the information required for preliminary planning of test programs and for preliminary layout of models and model supports which may be used in such programs. Appendix B (by Blair, B. Gloss and Donna Nystrom) presents estimated performance maps for the NTF.

*NASA, Langley Research Center, Hampton, VA, 23665

242 *Wigley, D. A., **Sandefur, P. G., Jr.; and **Lawing, P. L. **Preliminary Results on the Development of Vacuum Brazed Joints for Cryogenic Wind Tunnel Aerofoil Models.** Advances in Cryogenic Engineering (Materials), vol. 28, Aug. 10-14, 1981, pp. 893-903.

A81-44667#

The results of these initial experiments show that high strength void-free bonds can be formed by vacuum brazing of stainless steels using copper and nickel-based filler metals. In Nitronic 40, brazed joints have been formed with strengths in excess of the yield strength of the parent metal and even at liquid nitrogen temperatures the excellent mechanical properties of the parent metal are only slightly degraded. The poor toughness of 15-5 PH stainless steel at cryogenic temperatures is lowered even further by the presence of the brazed bonds investigated and it is highly unlikely that the technique would be used for any critical areas of aerofoil models intended for low-temperature service. Nevertheless, the potential advantages of this simplified method of construction still have attractions for use at ambient temperatures.

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**NASA, Langley Research Center, Hampton, VA, 23665

Contract NAS1-16000 (Research supported by Kentron, International, Inc., Univ. of Southampton, and NASA)

243 *Clausing, A. M. **An Experimental Investigation of Convective Losses From Solar Receivers, Final Rept.** Volume I, Executive Summary. University of Illinois TR-ME-TN-81-9180-3, Aug. 1981. 25 pp.

N83-10500#

The cryogenic test facility is described. A cryogenic environment provides a means of obtaining, simultaneously, large increases in both the Reynolds number and the Grashof number; hence, it provides an excellent tool for forced, natural, and combined convection heat transfer research. The Reynolds and Grashof numbers are increased with an ambient temperature of 80 K by factors of approximately 14 and 200, respectively, over those obtainable in a room temperature facility. The cryogenic environment virtually eliminates the influences of radiative heat transfer. The ability to vary the temperature in the test section greatly increases the range in the Reynolds and Grashof numbers that can be investigated with fixed model and test section dimensions. The cryogenic facility also provides an excellent environment for the investigation of the influences of property variations across the boundary layers.

*University of Illinois at Urbana-Champaign, Urbana, IL, 61801
Research Grant No. 87-9180

244 *Armstrong, E. S., and *Tripp, J. S. **An Application of Multivariable Design Techniques to the Control of the National Transonic Facility.** NASA TP-1887, Aug. 1981. 34 pp.

N81-29840#

The digital versions of optimal linear regulator theory and eigenvalue placement theory are applied to the Mach number control loop of the National Transonic Facility cryogenic wind tunnel. The control laws developed are evaluated on a nonlinear simulation of the tunnel process for a typical test condition and are found to significantly reduce the open loop time required to achieve a Mach number set point.

*NASA, Langley Research Center, Hampton, VA, 23665

24· *Ladson, Charles L., and *Ray, Edward J.: **Status of Advanced Airfoil Tests in the Langley 0.3-m Transonic Cryogenic Tunnel.** ACEE Project Oral Status Review, Dryden Research Center, Sept. 14, 1981. Advanced Aerodynamics — Selected NASA Research, NASA CP-2208, Dec. 1981, pp. 37-53.

N84-27664#

A joint NASA/U.S. industry program to test advanced technology airfoils in the Langley 0.3-m Transonic Cryogenic Tunnel (TCT) has been formulated under the Langley ACEE Project Office. The objectives of this program include providing U.S. industry an opportunity to compare their most advanced airfoils to the latest NASA designs by means of high Reynolds number tests in the same facility. At the same time, industry would gain experience in the design and construction of cryogenic models as well as experience in cryogenic test techniques. This paper presents the status and details of the test program. Typical aerodynamic results obtained, to date, are presented at chord Reynolds number up to 45×10^6 and are compared to results from other facilities and theory. Details of a joint agreement between NASA and the Deutsche Forschungs- und Versuchsanstalt fur Luft- and Raumfahrt e.V. (DFVLR) for tests of two airfoils are also included. Results of these tests will be made available as soon as practical.

*NASA, Langley Research Center, Hampton, VA, 23665

246 *Hall, Robert M., and *Adcock, Jerry B. **Simulation of Ideal-Gas Flow by Nitrogen and Other Selected Gases at Cryogenic Temperatures.** NASA TP-1901, Sept. 1981, 51 pp.

N81-32418#

The real gas behavior of nitrogen, the gas normally used in transonic cryogenic tunnels, is reported for the following flow processes: isentropic expansion, normal shocks, boundary layers, and interactions between shock waves and boundary layers. The only differences in predicted pressure ratio between nitrogen and an ideal gas which may limit the minimum operating temperature of transonic cryogenic wind tunnels occur at total pressures approaching 9 atm and total temperatures 10 K below the corresponding saturation temperature. These pressure differences approach 1 percent for both isentropic expansions and normal shocks. Alternative cryogenic test gases were also analyzed. Differences between air and an ideal diatomic gas are similar in magnitude to those for nitrogen and should present no difficulty. However, differences for helium and hydrogen are over an order of magnitude greater than those for nitrogen or air. It is concluded that helium and cryogenic hydrogen would not approximate the compressible flow of an ideal diatomic gas.

*NASA, Langley Research Center, Hampton, VA, 23665

247 *Polhamus, E. C., and *Boyden, R. P. **The Development of Cryogenic Wind Tunnels and Their Application to Maneuvering Aircraft Technology.** Presented as Paper No. 15 at the AGARD Symposium on Combat Aircraft Maneuverability, Florence, Italy, Oct. 5-8, 1981, 12 pp. In AGARD-CP-319.

N82-22196#
A82-13971#

Because of the strong influence of Reynolds number, Mach number, and aeroelasticity on the aerodynamics of combat aircraft in the high angle-of-attack range encountered during maneuvers, the unique capabilities of the new cryogenic wind tunnels offer the aircraft designer important new capabilities for validation of his design methodology as well as the ability to isolate various effects. This paper, therefore, discusses the cryogenic wind tunnel relative to its potential for advancing maneuvering aircraft technology. The first portion of the paper consists of a brief overview of the cryogenic wind-tunnel concept and the capabilities and status of the Langley cryogenic facilities. Included in this part is a review of the considerations leading to the selection of the cryogenic concept such as capital and operating costs of the tunnel, model and balance construction implications, and test conditions related to requirements specifically associated with maneuvering aircraft technology. Typical viscous, compressibility and aeroelastic effects encountered by maneuvering aircraft are illustrated and the unique ability of the cryogenic wind tunnels to isolate and investigate these parameters while simulating full-scale conditions is discussed. The status of the Langley cryogenic wind-tunnel facilities is reviewed and their operating envelopes described in relation to maneuvering aircraft research and development requirements. The final portion of the paper reviews the status of cryogenic testing technology development specifically related to aircraft maneuverability studies including force balances and buffet measurement techniques. Included are examples of research carried out in the Langley 0.3-m Transonic Cryogenic Tunnel to verify the various techniques.

*NASA, Langley Research Center, Hampton, VA, 23665

248 *Lassiter, W. S. **Design Predictions for Noise Control in the Cryogenic National Transonic Facility.** Noise Control Engineering, vol. 17, Sept.-Oct. 1981, pp. 76-84. (A paper on this subject was presented at Noise-Con 81 at North Carolina State Univ., June 8-10, 1981, and is in their Proceedings, pp. 121-124. For a shortened form see Astronautics and Aeronautics, Feb. 1981, p. 45.)

A82-12025

Noise control in the National Transonic Facility — a cryogenic wind tunnel — has been examined in terms of acoustical design criteria, drive-fan noise and exhaust system noise. A duct lining with two layers of perforated sheeting and a gas-filled honeycomb core was selected for attenuating drive-fan noise. With the exception of attenuation peaks, attenuation of the lining was found to experimentally agree with predicted values at 20°C air temperatures. Exhaust system noise will be attenauted with a large muffler used in conjunction with a 6.1-m high acoustical enclosure. Fan noise from the fan-ejector system will be attenuated by fan silencers and the acoustic enclosure.

*NASA, Langley Research Center, Hampton, VA, 23665

249 *Polhamus, E. C. **The Large Second Generation of Cryogenic Tunnels.** Astronautics and Aeronautics, vol. 19, Oct. 1981, pp. 38-51.

A81-48720#

Developmental histories and proven or projected operational capabilities are presented for wind tunnels, already operational or nearing completion, whose stream fluid is cryogenic and permits the testing of advanced transonic and supersonic aircraft designs at Reynolds numbers of up to 120 million. These facilities include (1) the NASA/Langley National Transonic Facility (NTF), which can employ a conventional fan drive because of the drive power reductions permitted by the cryogenic nitrogen stream fluid, (2) the Douglas Aircraft 4.0-ft trisonic tunnel, converted from conventional operation, and (3) the European Transonic Windtunnel, which is based on the fan-driven cryogenic pressure tunnel concept. Also covered are national research facilities in France, Japan, Britain, and West Germany. Attention is given the integration of digital control and data acquisition and processing capabilities into the cryogenic facilities, such as the four identical computers of the NTF which are to increase productivity and reduce operating costs.

*NASA, Langley Research Center, Hampton, VA, 23665

250 *Clark, G. L., Jr. **Cryogenic Modeling by Combined Convection From a Vertical Cylinder in a Horizontal Flow.** Univ. of Ill., Ph.D. thesis, Oct. 1981, 209 pp.

N82-32632#

Prediction of the convective loss from solar thermal-electric receivers is not presently feasible since the scientific basis for such a prediction is not available. These receivers will typically operate in

the combined convection region ($Gr_L/Re_D^2 \approx 1$) with Reynolds numbers, Re, above 10^6 and Grashof numbers, Gr, exceeding 10^{11}, well above previously reported experimental data. A novel heat transfer technique, the use of cryogenic temperatures for convective modeling, was used in the present investigation to significantly extend the region of measured data for combined convection from a vertical cylinder in a horizontal flow. Reynolds numbers above 5×10^5, with Grashof numbers above 10^{11}, were achieved in a cryogenic heat transfer tunnel which was constructed for this research.

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Research supported by Sandia Labs, Livermore, CA

251 *Tripp, John S. **An Algorithm for Minimum-Cost Set-Point Ordering in a Cryogenic Wind Tunnel.** NASA TP-1923, Nov. 1981. 30 pp.

N82-11090#

An algorithm for minimum-cost ordering of set points in a cryogenic wind tunnel is developed. The procedure generates a matrix of dynamic state-transition costs, which is evaluated by means of a single-volume lumped model of the cryogenic wind tunnel and the use of some idealized minimum-cost state-transition control strategies. A branch and bound algorithm is employed to determine the least costly sequence of state transitions from the transition-cost matrix. Some numerical results based on data for the National Transonic Facility are presented which show a strong preference for state transitions that consume no coolant. Results also show that the choice of the terminal set point in an open ordering can produce a wide variation in total cost.

*NASA, Langley Research Center, Hampton, VA, 23665

252 *Clausing, A. M., and *Kempka, S. N. **The Influences of Property Variations on Natural Convection From Vertical Surfaces.** ASME Winter Annual Meeting, Nov. 15-20, 1981, Washington, D.C., and published in the ASME "Natural Convection," HTD Vol. 16, 1981. Also published in Journal of Heat Transfer, Vol. 103, No. 4, Nov. 1981, pp. 609-612.

The objective of this paper is to show the influences of property variations in natural convection. Heat transfer from a vertical isothermal, heated surface to gaseous nitrogen is experimentally investigated. The ambient temperature, T_∞, is varied in order to cover a large range of the Rayleigh number and also to enable the generation of large values of this parameter. The range $80\,K < T_\infty < 320\,K$ results in Rayleigh numbers between 10^7 and 2×10^{10} for the 0.28 m model. By using a cryogenic environment, large ratios of the absolute temperature of the wall to the ambient temperature, T_w/T_∞, are generated without the results being masked by radiative heat transfer. The range $1 < T_w/T_\infty < 2.6$ is investigated. Variable properties cause dramatic increases in heat transfer rates in the turbulent regime, and virtually no influence is seen in the laminar regime. The results obtained correlate extremely well with the addition of a single parameter T_w/T_∞.

*University of Illinois at Urbana-Champaign, Urbana, IL, 61801

Grant No. 87-9180, DOE Subcontract

253 *Lawing, Pierce L. **Vacuum-Brazed Joints for Cryogenic Wind-Tunnel Models.** Research and Technology -- Annual Report of the Langley Research Center, NASA TM-83221, Nov. 1981, p. 7.

N82-13043 (p. 7)

Nitronic 40 has been chosen for construction of pilot models to be used in the NTF cryogenic tunnel. The ability to form bonded joints in Nitronic 40 is discussed and results are described. Highlights of major accomplishments and applications are presented in this annual report.

*NASA, Langley Research Center, Hampton, VA, 23665

254 *Morel, J. P. **A Progress Report on the European Transonic Windtunnel Project** (Le Projet de Soufflerie Transsonique Européenne ETW - Etat actual). Association Aeronautique et Astronomique de France, Colloque d'Aerodynamique Appliquee, 18th, Poitiers, France, Nov. 18-20, 1981. ONERA-TP-1981-121, 1981. 24 pp. (In French.)

A82-19737#

An interim report on the design for a European Transonic Windtunnel, being built by the cooperative efforts of West Germany, Britain, and the Low Countries is presented and details of the partially completed prototype wind tunnel are provided. The ETW will be a cryogenic, nitrogen gas installation for examining flows at high Reynolds numbers, and consultations are continuing with NASA on the cryogenic technology. The full test channel will have a $2.4\times2\,m^2$ cross section, with a pressure variance between 1.25-4.5 bars. Temperatures will range from 120-168 K at Mach numbers up to 1.7, and equipment altering the incidence angle of test models at a rate of 4 deg/sec is intended. A pilot ETW is under construction, with a cross-section of 0.27×0.23 m, and is being used to verify the aerodynamic performance of the flow circuit, the responses to Mach number, pressure, and temperature, and the control circuits.

*ONERA, BP 72, 92322 Chatillon Cedex, France

255 *Johnson, C. D. **Study of Nonadiabatic Boundary-Layer Stabilization Time in a Cryogenic Tunnel for Typical Wing and Fuselage Models.** Journal of Aircraft, vol. 18, no. 11, Nov. 1981, pp. 913-919.

AIAA Paper 80-0417

Note: For an earlier form of this paper and an abstract see entry 177 in this bibliography.

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256 *Murthy, A. V.; **Johnson, C. B.; **Ray, E. J., and **Lawing, P. L.: **Recent Sidewall Boundary-Layer Investigations With Suction in the Langley 0.3-m Transonic Cryogenic Tunnel.** AIAA 20th Aerospace Sciences Meeting, Orlando, Florida, Jan. 11-14, 1982. 11 pp.

AIAA-82-0234 A82-17858#

An experimental and theoretical study of the Langley 0.3-m Transonic Cryogenic Tunnel (TCT) sidewall boundary-layer with and without suction, has been made. Without suction, the boundary-layer displacement thickness at a station ahead of the model varied from about 1.6 mm to 1.3 mm over a Reynolds number range of 20 to 200×10^6/m at Mach numbers from 0.30 to 0.76. Measured velocity profiles correlated using the defect law of Hama. The boundary-layer displacement thickness decreased when suction was applied, however, after suction of about 2 percent of test section mass flow, the change in the thickness was small. A comparison of the measured suction effectiveness with finite difference and integral methods of boundary-layer calculation showed that both the methods predicted the right trend over the range of suction velocities (up to $v_w/u_e = -0.02$).

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257 L'ONERA à l'heure des Souffleries Cryogéniques. (ONERA now has one of the cryogenic wind tunnels.) Aviation (International) Magazine No 818 Jan 15 31 1982 pp 28 32 (In French)

ONERA has completed its transformation of the T2 tunnel. This tunnel located at Centre d'Etudes et de Recherches de Toulouse (CERT), operates at very low temperatures in the neighborhood of 100 kelvin (173°C). The facility is described. Insulating materials are discussed. The tunnel can attain a Reynolds number of 37 million with models of 150 mm. The wind tunnel also has adaptable walls.

258 *Beck, J W **Cryogenic-Wind-Tunnel Technology — A Way to Measurement at Higher Reynolds Numbers.** (Kryo-Windkanal-Technologie-Ein Weg zur Messung bei höheren Reynolds-Zahlen.) In Publication on the occasion of the 65th birthday of Prof. Dr.-Ing. Erich Truckenbrodt, Scientific Colloquium, Technische Universitat Munchen, Munich, West Germany, Feb. 1, 1982, Reports (A83-46482). Munich, Technische Universitat Munchen, 1982, pp 53-87 (In German.) For English translation, see NASA TM-77481, May 1984

A83-46484# (German)
N84-34451# (English)

The goals, design, problems, and value of cryogenic transonic wind tunnels being developed in Europe are discussed. The disadvantages inherent in low-Reynolds-number (Re) wind-tunnel simulations of aircraft flight at high Re are reviewed, and the cryogenic tunnel is shown to be the most practical method to achieve high Re. The design proposed for the European Transonic Windtunnel (ETW) is presented: parameters include cross-section of 4 m² operating pressure of 5 bar, temperature of 110-120 K, maximum Re of 40×10^6, liquid N_2 consumption of 40,000 metric tons/year, and power of 39.5 MW. The smaller Cologne subsonic tunnel being adapted to cryogenic use by DFVLR for preliminary studies is described. Problems of configuration, materials and liquid-N_2 evaporation and handling, and the research underway to solve them are outlined. The benefits to be gained by the construction of these costly installations are seen more in applied aerodynamics than in basic research in fluid physics. The need for parallel development of both high-Re tunnels and computers capable of performing high—Re numerical analysis is stressed.

*DFVLR, Oberpfaffenhofen, West Germany (FRG)

259 *Teague, E. C.; *Vorburger, T. V.; *Scire, F. E.; *Baker, S. M.; *Jensen, S. W.; *Trahan, C.; and **Gloss, B. B.: **Evaluation Methods for Characterizing Surface Topography of Models for High Reynolds Number Wind-Tunnels.** AIAA 12th Aerodynamic Testing Conference, Williamsburg, Va., Mar. 21-24, 1982. 6 pp. Technical papers, pp. 246-251.

AIAA-82-0603 A82-24675#

Because of the high Reynolds number of the National Transonic Facility, (NTF), and the attendant thin boundary layers, the National Aeronautics and Space Administration is reexamining aerodynamic effects related to model surface topography definition. There are no data which demonstrate that the stylus instruments used by model fabrication shops accurately determine the topography of surfaces typical of NTF models. This paper describes current work at the National Bureau of Standards, sponsored by NASA, to evaluate the performance of stylus instruments for this application and to develop a light scattering instrument which will yield accurate characterizations of the surface microtopography and overcome the problems associated with stylus profilometry.

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**NASA, Langley Research Center, Hampton, VA, 23665

260 *Lynch, F T. and *Patel, D R **Some Important New Instrumentation Needs and Testing Requirements for Testing in a Cryogenic Wind Tunnel Such as the NTF.** AIAA 12th Aerodynamic Testing Conference, Williamsburg, Va., Mar 21-24, 1982. 13 pp.

AIAA-82-0605

A great deal of effort has been focused on solving the actual construction and facility-related problems of cryogenic wind tunnels such as the National Transonic Facility (NTF). In contrast, however, inadequate attention has been given to the development of solutions to important user-related problems unique to cryogenic wind tunnels. To be able to exploit the potential advantage of the very high Reynolds number capability that will be provided by the NTF, several issues regarding instrumentation requirements and testing techniques must be addressed now. Two of the most important issues, largely ignored to date, concern the need for new boundary-layer transition fixing and detection methods for NTF models, and the need for precise model thermal conditioning and associated thermal control instrumentation. Another requirement which must be addressed is the need to provide provisions to establish model support interference effects. The rationale for these requirements in a cryogenic wind tunnel, and the urgency relative to the NTF is presented. All of these requirements will result in substantially higher model and testing costs than had been previously anticipated. Recommendations for near-term action by the technical community interested in effectively using the NTF are offered.

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261 *Fancher, M. F. **Aspects of Cryogenic Wind Tunnel Testing Technology at Douglas.** AIAA 12th Aerodynamic Testing Conference, Williamsburg, Va., March 21-24, 1982. 11 pp.

AIAA-82-0606

The need for high-Reynolds number transonic aerodynamic testing capability appears near fulfillment with introduction of the cryogenic National Transonic Facility (NTF). To date, much emphasis has been placed on development of facility-related hardware and technology. Analysis and experience have shown, however, that a considerable number of user-related problems remain to be resolved before the NTF may be used either efficiently or effectively. The present paper describes the approach and experience at Douglas in further defining and seeking solutions to some of the outstanding testing problems facing users of the NTF. Subjects discussed include development of boundary-layer transition detection instrumentation, maintenance of model temperature tolerances, test section optical access, model materials, and model fabrication methods. (Copies may be secured from the author.)

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262 *Hunter, W. W., Jr., and *Foughner, J. T., Jr., Editors **Flow Visualization and Laser Velocimetry for Wind Tunnels.** NASA CP-2243, Sept. 1982, 354 pp. Selected items follow in this bibliography.

N82-32663#

The proceedings of a workshop held on March 25-26, 1982, at NASA Langley Research Center, Hampton, VA, are presented. The need for flow visualization and laser velocimetry were discussed. The purpose was threefold: (1) provide a state-of-the-art overview; (2) provide a forum for industry, universities, and government agencies to address problems in developing useful and productive flow visualization and laser velocimetry measurement techniques; and (3) provide discussion of recent developments and applications of flow visualization and laser velocimetry measurement techniques

and instrumentation systems for wind tunnels including the Langley 0.3-Meter Transonic Cryogenic Tunnel

*NASA, Langley Research Center, Hampton, VA, 23665

263 *Crowder, James P. **Surface Flow Visualization Using Indicators.** Flow Visualization and Laser Velocimetry for Wind Tunnels, paper no. 5, NASA-CP-2243, Sept 1982, pp. 37-46 (Presented Mar 1982.)

N82-32668#

Surface flow visualization using indicators in the cryogenic wind tunnel which requires a fresh look at materials and procedures to accommodate the new test conditions is described. Potential liquid and gaseous indicators are identified. The particular materials illustrate the various requirements an indicator must fulfill. The indicator must respond properly to the flow phenomenon of interest and must be observable. Boundary layer transition is the most important phenomenon for which flow visualization indicators may be employed. The visibility of a particular indicator depends on utilizing various optical or chemical reactions. Gaseous indicators are more difficult to utilize, but because of their diversity may present unusual and useful opportunities. Factors to be considered in selecting an indicator include handling safety, toxicity, potential for contamination of the tunnel, and cost.

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264 *Rhodes, D. B., and *Jones, S. B. **Flow Visualization in the Langley 0.3-Meter Transonic Cryogenic Tunnel and Preliminary Plans for the National Transonic Facility.** Flow Visualization and Laser Velocimetry for Wind Tunnels, paper no. 14, NASA CP-2243, Sept. 1982, pp. 117-132. (Presented Mar. 1982.)

N82-32677#

Design problems associated with the integration of flow visualization in cryogenic facilities are discussed. The possible effects from the cryogenic environment (i.e., window distortion due to thermal contraction, both in the mounts and in the window material itself, and turbulence in the flow due to injected LN_2) are examined. The flow visualization techniques studied are schlieren, shadowgraph, moiré deflectometry, and holographic interferometry. The test beds for this work are a Langley in-house cryogenic test chamber and the 0.3-m Transonic Cryogenic Tunnel.

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265 *Snow, W. L.; *Burner, A. W.; and *Goad, W. K.: **"Seeing" Through Flows in Langley's 0.3-Meter Transonic Cryogenic Tunnel.** Flow Visualization and Laser Velocimetry for Wind Tunnels, paper no. 15, NASA CP-2243, Sept. 1982, pp. 133-147. (Presented Mar. 1982.)

N82-32678#

Viewing problems associated with the measurement of model deformation in cryogenic wind tunnels are discussed. Tests were conducted in the Langley 0.3-m Transonic Cryogenic Tunnel to assess viewing capabilities through the flow field. The effects of condensation and turbulent boundary layers are discussed and a modelling procedure for image degradation is described.

*NASA, Langley Research Center, Hampton, VA, 23665

266 *Burner, A. W.; *Snow, W. L.; *Goad, W. K.; *Helms, V. T.; and *Gooderum, P. B.: **Flow Field Studies Using Holographic Interferometry at Langley.** Flow Visualization and Laser Velocimetry for Wind Tunnels, paper no. 20, NASA CP-2243, Sept. 1982, pp. 193-204 (Presented Mar. 1982.)

N82-32682#

Some of the uses of holographic interferometry at Langley Research Center both for flow visualization and for density field determinations are described and tests in cryogenic flows at the Langley 0.3-m Transonic Cryogenic Tunnel are discussed. Experimental and theoretical fringe shift data are compared.

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267 *Gartrell, Luther R.: **Laser Doppler Velocimetry Application in the Langley 0.3-Meter Transonic Cryogenic Tunnel.** Flow Visualization and Laser Velocimetry for Wind Tunnels, paper no. 34, NASA CP-2243, Sept. 1982, pp. 323-334 (Presented Mar 1982)

N82-32696#

The problems and the potential use of a nonintrusive flow velocity measuring technique in the Langley 0.3-m, Transonic Cryogenic Tunnel (TCT) were investigated. A laser velocimeter (LV) was used. It was concluded that free-stream velocity measurements can be successfully made in the Langley 0.3-m TCT using a low-power (15-mW) LV system. The measured and calculated mean velocities typically agreed within one percent. The overall normalized standard deviation was less than one percent. Tunnel vibration and temperature had no detrimental effects on the optical system. It is recommended that the LV work should be further investigated for future use in the Langley 0.3-m TCT.

*NASA, Langley Research Center, Hampton, VA, 23665

268 *Honaker, W. C.: **Velocity and Flow Angle Measurements in the Langley 0.3-Meter Transonic Cryogenic Tunnel Using a Laser Transit Anemometer.** Flow Visualization and Laser Velocimetry for Wind Tunnels, paper no. 35, NASA CP-2243, Sept. 1982, pp. 335-342. (Presented Mar. 1982.)

N82-32697#

The Laser Transit Anemometer (LTA) system is described. In the LTA system two parallel laser beams of known separation and cross sectional area are focussed at the same location or plane. When a particle in a flow field passes through both beams and the time is recorded for its transit (time of flight), its velocity can be calculated knowing the distance between the beams. By rotating the two beams (spots) around a common center and recording the number of valid events (a particle which passes through both spots in the proper sequence) at each angle the flow angle can be determined by curve fitting a predetermined number of angles or points and calculating the peak of what should be a Gaussian curve. The best angle or flow angle is defined as the angle at which the maximum number of valid events occurs. The LTA system functioned properly although conditions were less than desirable.

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269 *Hunter, W. W., Jr.; *Gartrell, L. R.; and *Honaker, W. C.: **Some NTF Laser Velocimeter Installation and Operation Considerations.** Flow Visualization and Laser Velocimetry for Wind Tunnels, paper no. 36, NASA CP-2243, Sept. 1982, pp. 343-358. (Presented Mar. 1982.)

N82-32698#

Two velocimeter techniques were considered as potential candidates for achieving the flow field angularity measurements. The first was the fringe laser Doppler velocimeter, (LDV). A great deal of experience was obtained with this approach at Langley and the literature is rich with papers describing [illegible]rimental applications and system performance details. That is, many velocity flow field measurements were conducted with the LDV but not with high resolution precise angularity measurements. The second candidate considered was the two-spot laser transit anemometer, (LTA). This approach was not as extensively used as the LDV technique, but

literature does contain experimental applications and system performance details. Again, a lack of high resolution, high precision angularity measurements is noted for the LTA. The results of the study suggested that the LDV and LTA tests and other efforts did not reveal any fundamental problems that would suggest that laser velocimetry is not a viable diagnostic technique for the National Transonic Facility. However, there are a number of engineering problems that need to be solved.

*NASA, Langley Research Center, Hampton, VA, 23665

270 *Michel, R. and *Mignosi, A. **Adaptation and First Cryogenic Operation of T2 ONERA/CERT Wind Tunnel.** La Recherche Aerospatiale (English Edition), No 2, Mar.-Apr. 1982, pp. 75-85.

A82-42531#
N84-13143#

A description is given of the transformation of the ONERA/CERT induction-driven transonic wind tunnel into a blowdown, cryogenic wind tunnel which employs high pressure air as a driving gas and liquid nitrogen as a coolant. An analysis of results from the first series of low temperature tests shows that the combination of induction and cryogenics yields steady and well defined low temperature flows at transonic Mach numbers, with temperatures as low as 100 K and Reynolds numbers from 3 million to over 30 million. Attention is given to the design details of the liquid nitrogen supply and injection systems, as well as the performance levels achieved.

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271 *Wigley, D. A.: **The Metallurgical Structure and Mechanical Properties at Low Temperatures of Nitronic 40, With Particular Reference to Its Use in the Construction of Models for Cryogenic Wind Tunnels.** NASA CR-165907, Apr. 1982. 66 pp.

N82-30375

Nitronic 40 was chosen for the construction of Pathfinder I, an R & D model for use in the National Transonic Facility, because of its good published mechanical properties at cryogenic temperatures. Nitronic 40 delivered to LaRC, McDonnell Douglas and Lockheed was, however, found to contain delta ferrite and to be in a sensitized condition. Heat-treatments carried out at LaRC to remove residual stresses also caused further sensitization. Experiments showed that heat-treatment followed by cryoquenching removed the sensitization without creating residual stresses. Heat-treatment at temperatures of 2200°F was used to remove the delta ferrite but with little success and at the cost of massive grain growth. The implications of using degraded Nitronic 40 for cryogenic wind tunnel models are discussed, together with possible acceptance criteria. It is suggested that in the future it will be necessary to implement a policy of purchasing top quality materials for cryogenic wind tunnel models.

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Contract NAS1-16000

272 AGARD Fluid Dynamics Panel: **Windtunnel Capability Related to Test Sections, Cryogenics, and Computer-Windtunnel Integration.** Apr. 1982.

Introduction — Dietz, R.O.[1]
Appendix 1 — Binion, T. W., Jr.[2]; Chevallier, J. P.[3]; and Laster, M. L.[4] (editor): Report of the Conveners' Group on **Transonic Test Sections.**
Appendix 2 — McKinney, L. W.[5]; North, R. J.[6]; and Polhamus, E. C.[7] (editor): Report of the Conveners' Group on **Cryogenic Test Technology.**
Appendix 3 — Firmin, M. C. P.[8]; Potter, J. L.[4]; and Green, J. E.[9] (editor): Report of the Conveners' Group on **Integration of Computers and Wind Tunnel Testing.** AGARD-AR-174, Apr. 1982. 64 pp.

ISBN-92-835-1420-3 N82-29334#

The Advisory Report includes the results of six meetings sponsored by the Fluid Dynamics Panel and conclusions drawn from the reports prepared by the meeting chairmen. In each of the three subject areas, meetings were convened in the U.S. and Europe, with the results being combined by the chairmen. Applications of the technology discussed in this report can afford large improvements in wind tunnel capability and effectiveness.

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[6]Technical Group, ETW, NLR, Amsterdam, The Netherlands
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[8]Aerodynamics Department, R.A.E., Farnborough, Hampshire GU14 6TD, U.K.
[9]Ministry of Defence, 1 St. Giles High Street, London WC2 LD, U.K.

273 *Hornung, H.; *Hefer, G.; *Krogmann, P.; and *Stanewsky, E.: Transsonische Kryo-messtrecke fuer den Goettinger Rohrwindkanal **(Transonic Cryogenic Test Section for the Goettingen Tube Facility.)** DFVLR Report No. IB-222-82 A19, May 3, 1982, 19 pp. (For an English translation, see entry 317 in this bibliography.)

The design of modern aircraft requires the solution of problems related to transonic flow at high Reynolds numbers. To investigate these problems experimentally, it is proposed to extend the Ludwieg tube facility in Goettingen by adding a transonic cryogenic test section. After stating the requirements for such a test section, the technical concept is briefly explained and a preliminary estimate of the costs is given.

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274 *Young, C. P., Jr.; and *Gloss, B. B., compilers: **Cryogenic Wind Tunnel Models — Design and Fabrication.** NASA CP-2262, Mar. 1983. 266 pp. Proceedings of a workshop held at NASA Langley Research Center, Hampton, VA, on May 5-9, 1982, are presented.

N83-18748#

The principal motivating factor was the National Transonic Facility (NTF). Since the NTF can achieve significantly higher Reynolds numbers at transonic speeds than other wind tunnels in the world, and will therefore occupy a unique position among ground test facilities, every effort is being made to ensure that model design and fabrication technology exists to allow researchers to take advantage of this high Reynolds number capability. Since a great deal of experience in designing and fabricating cryogenic wind tunnel models does not exist, and since the experience that does exist is scattered over a number of organizations, there is a need to bring existing experience in these areas together and share it among all intersted parties. Representatives from government, the airframe industry, and universities are included. For individual titles, see N83-18749 through N83-18769.

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Overview of National Transonic Facility Model Technology Program. McKinney, L. W., pp. 1-10.

Model Systems Criteria. Young, Clarence P., Jr., pp. 11-18. N83-18749#

275 *Wigley, D. A. **Metallurgical Problems Encountered with Nitronic 40 Stainless Steel Intended for the Fabrication of Aerofoil Models for Cryogenic Wind Tunnels.** International Cryogenic Materials Conference, May 11-14, 1982, Kobe, Japan, pp. 25-28.

Nitronic 40, a 21 chromium-6 nickel-9 manganese-0.4 nitrogen austenitic stainless steel, was chosen for fabricating aerofoil models for cryogenic wind tunnels due to a combination of its high strength and toughness at cryogenic temperatures and its ready availability in the required product forms. Material delivered to NASA Langley and to a number of other U.S. Aerospace Corporations was, however, found to contain significant amounts of delta ferrite and to be in a sensitized condition. Heat-treatments carried out at LaRC to remove residual stresses also caused further sensitization. Experiments showed that heat-treatment followed by cryoquenching removed the sensitization without creating residual stresses. Heat-treatment at temperatures of 2200°F was used to remove the delta ferrite but with little success and at the cost of massive grain growth.

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Contract NAS1-16000

276 *Kilgore, Robert A. **The Cryogenic Wind Tunnel for High Reynolds Number Testing.** Ninth International Cryogenic Engineering Conference, Kobe, Japan, May 11-14, 1982, pp. 389-394

A82-33317

An improved way to increase the Reynolds numbers capability of wind tunnels has been developed at the Langley Research Center. Cooling the test gas to cryogenic temperatures by spraying liquid nitrogen into the tunnel circuit increases Reynolds number with no increase in dynamic pressure and a reduction in drive power. In addition, the ability to vary the temperature of the test gas independently of pressure and Mach number allows for the first time the independent determination of Reynolds number, Mach number, and aeroelastic effects. A new fan-driven transonic cryogenic tunnel being built at the Langley Research Center will provide an order of magnitude increase in Reynolds number capability over existing transonic tunnels in the United States when it is completed later this year.

*NASA, Langley Research Center, Hampton, VA 23665

277 *Ito, Kenkichi, and *Saji, Nobuyoshi. **S-Foam Applied to Cryogenic Wind Tunnel.** International Cryogenic Materials Conference, Kobe, Japan, May 11-14, 1982, pp. 455-458

A82-33316

Ishikawajima-Harima Heavy Industries Co., Ltd. is the sole manufacturer in Japan of cryogenic wind tunnels which are for research in the high Reynolds number regions. We have built three such tunnels, of which special attention will be directed to the one that we have delivered recently to the University of Tsukuba as it features our own internal insulation that promises a great saving of coolant and other advantages. A special plastic foam for cryogenic temperature, called S-foam, is used as the innermost lining of the tunnel body. This paper provides mainly the characteristics of this foam.

*Research Institute, Ishikawajima-Harima Heavy Industries Co., Ltd., Tokyo, Japan

278 *Kilgore, Robert A., and **Dress, David A. **The Cryogenic Wind Tunnel for High Reynolds Number Testing.** An informal lecture presented at the National Aerospace Laboratory, Chofu, Tokyo, Japan, May 20, 1982, 36 pp.

A82-33320#

This informal lecture provides an overview of the development of cryogenic wind tunnels and their application to high Reynolds number testing. The major portion is devoted to a review of the theory and advantages of cryogenic tunnels and a brief description of three of the applications of the cryogenic tunnel concept, the Low-Speed Cryogenic Tunnel built at Langley in 1972, the 0.3-m Transonic Cryogenic Tunnel built at Langley in 1973, and the National Transonic Facility (NTF) presently under construction at Langley and expected to be in operation before the end of 1982.

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**Kentron International, Inc., Hampton Technical Center, Hampton, VA 23665

279 *Ray, E. J.: **A Review of Reynolds Number Studies Conducted in the Langley 0.3-m Transonic Cryogenic Tunnel.** AIAA/ASME 3rd Joint Thermophysics, Fluids, Plasma and Heat Transfer Conference, St. Louis, Mo., June 7-11, 1982. 14 pp.

AIAA-82-0941 A82-34007#

The Langley 0.3-m Transonic Cryogenic Tunnel (TCT) was first placed in operation as a pilot transonic cryogenic wind tunnel at NASA's Langley Research Center in 1973. As a result of its successful operation as the world's first transonic cryogenic pressure tunnel and its potential as a powerful new research tool, the pilot tunnel was later reclassified as a "permanent" facility. During the period of operation of the 0.3-m TCT, an emphasis has been placed on the determination of Reynolds number effects on a wide variety of both two-dimensional and three-dimensional configurations. This paper reviews some of the Reynolds number studies which have been conducted in the 0.3-m TCT and presents selected highlights obtained from these investigations.

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280 *Takashima, Kazuaki; *Sawada, Hideo; and *Aoki, Takeo: **A Survey of the Three-Dimensional High Reynolds Number Transonic Wind Tunnel.** (Koku Gijutsu Kenkyujo Shiryo). English translation of Japanese report, NAL-TM-440, Aug. 1981. NASA TM-76931, June 1982. 85 pp.

N83-23324#

Facilities for aerodynamic testing of airplane models at transonic speeds and high Reynolds numbers are surveyed. The need for high Reynolds number transonic testing is reviewed, using some experimental results. Some new approaches to high Reynolds number testing, i.e. the cryogenic wind tunnel, the induction driven wind tunnel, the Ludwieg tube, the Evans clean tunnel and the hydraulic driven wind tunnel are described. The level of development of high Reynolds number testing facilities in Japan is then discussed.

*National Aerospace Lab., Tokyo, Japan

NASA Contract NASw-3541.

281 *Hall, R. M.; **Dotson, E. H.; and ***Vennemann, D. H.: **Homogeneous and Heterogeneous Condensation of Nitrogen in Transonic Flow.** Presented at the 13th International Symposium on Rarefied Gas Dynamics, Novosibirsk, USSR, July 5-9, 1982, 12 pp. (This paper was also given as Paper #24, at the Cryogenic Technology Review Meeting in Amsterdam, Sept. 15-17, 1982).

A82-43258#

Onset of both homogeneous and heterogeneous nucleation for nitrogen gas has been measured in the Langley 0.3-m Transonic Cryogenic Tunnel. Homogeneous nucleation data have been taken using a DFVLR CAST-10 airfoil and are used to evaluate classical liquid droplet theory and several proposed corrections to it. A correction for differences in translational energy states between the droplet and the bulk liquid due to either Reiss (1977) or Kikuchi (1977) achieves good agreement between the predicted onset of nucleation and the data. Good agreement is also found using a Tolman constant of 0.25×10^{-10} m. Onset of heterogeneous nucleation on preexisting seed particles in the flow has also been studied, and preliminary estimates of seed size and number are 0.25×10^{-8} m and 3.0×10^{12} per kilogram of the gas. It is shown that this preexisting seed population is insufficient to influence the observed onset of homogeneous nucleation.

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282 *Wagner, Bernhard: **Estimation of Simulation Errors and Investigations of Operating Range Extensions for the European Transonic Windtunnel (ETW). Final Rept., March 1981.** Rept no BMFT-FB-W-82-003, July 1982. 162 pp. (In English.)

N83-11152#

The influence of viscous effects in combination with real gas effects and heat transfer at not correctly cooled model surfaces is investigated with respect to the simulation accuracy in the planned cryogenic European Transonic Windtunnel ETW. Changes in separation behavior and skin friction are calculated for the transonic shock-wave turbulent boundary-layer interaction by solving the full Navier-Stokes equations numerically and for profile flows by use of a nonadiabatic boundary-layer method. Both metods include a description of the real gas behavior by the Beattie-Bridgeman equation. The results show no considerable differences for the separation behavior although always small systematic deviations in skin friction occur. In particular, the shock boundary-layer interaction process does not exhibit a special sensitivity. Two-dimensional calculations presented for inviscid transonic flows with equilibrium condensations reveal that small amounts of condensate are admissible without affecting the accuracy of the measurements; deviations become first visible for the drag coefficient. Concerning the possible operating range extensions for the ETW due to the utilization of a favorable supersaturation effect, the presently provided computer program is capable of predicting the condensation onset and development including real gas equations in the flow calculation. The program has been verified by application to hypersonic nitrogen jets with condensation corresponding to ETW stagnation conditions. But experimental results obtained by duplicating a typical ETW streamline are still needed to make the predictions fully reliable for ETW conditions. Furthermore, the theoretical results with respect to equilibrium condensation lead to additional validation of the streamline duplication idea.

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This research was sponsored by the German Ministry of Research and Technology under support number LVW 7901 and by the Technical Group ETW, Amsterdam, under contract ETW/79/01/68730/143963.

283 *Wagner, B.: **Estimation of Simulation Errors in the European Transonic Windtunnel (ETW).** Presented at the 13th Council of the Aeronautical Sciences, and in Proceedings of AIAA Aircraft Systems and Technology Conference, Seattle, Wash., August 22-27, 1982, vol. 1, pp. 731-740.

ICAS-82-5.43 A82-40950#

Simulation errors in cryogenic wind tunnels caused by real gas effects, changes in viscosity and heat conductivity characteristics at low temperatures, heat transfer, and local condensation are estimated theoretically. For this purpose viscous effects and heat transfer influences in transonic high Reynolds number turbulent flows are calculated by solving numerically the full Navier-Stokes equations for shock wave boundary layer interactions and by calculating boundary layers on airfoils, real gas equations of state and nonadiabatic walls being included in both procedures. Equilibrium condensation approximating the case of heterogeneous nucleation is investigated in transonic airfoil flows by means of numerical solutions of the full inviscid Euler equations. The separation behavior is shown not to be sensitive to real gas effects and small amounts

of heat transfer. The condensation influence is primarily shown by a considerable drag increase.

*Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

This research was sponsored by the German Ministry of Research and Technology under support number LVW 7901 and by the Technical Group ETW, Amsterdam, under contract ETW/79/01 68730/143963.

284 *Gobert, J. L., and *Mignosi, A. **Studies on the Cryogenic Induction Driven Wind-Tunnel T2.** Paper no. 1 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 19 pp.

N83-28004#

The transonic induction driven wind-tunnel T2, with a testing section of 38×40 cm² pressurized up to 6 bars was transformed into a cryogenic system in 1981. The airflow cooling is provided by a parietal injection of liquid nitrogen in the wind-tunnel. An internal insulation preserves most of the tunnel elements and works with runs which last up to one minute. The method used for the run starting and the automatic control of the airflow parameters is described. A simplified process model allows a mini-computer centralizing all useful data to generate in real time the commands to initate and stabilize the desired temperature and pressure values. The results defining the installation performances and airflow qualities are presented.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

285 *Dubois, M. **Feasibility Study On Strain Gauge Balances for Cryogenic Wind Tunnels at ONERA.** Paper no. 2 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. ONERA-TP-1982-87, 1982. 20 pp.

A83-14539#

Ten dynamometric test pieces and a three-component sting balance were used in a study of cryogenic wind tunnel strain gauge technology, where the test pieces were fabricated from different materials and fitted with two or three bridges composed of various kinds of strain gauges. The testing of the pieces under bending stresses reached a strain level of 1 mm/m, with cryogenic chamber temperatures in the 100-300 K range. On the basis of test results, materials were selected for the construction of the three-component balance, with balance architecture and gauge equipment designed to reduce the influence of temperature variations to a negligible level. The balance's design allows it to be fitted with controlled heating devices, and will be calibrated in both cold and heated versions prior to certification trials in the ONERA/CERT cryogenic wind tunnel.

*ONERA, Modane Test Center, Modane, Savoie, France

286 *Francois, G. **Thermal Behavior and Insulation of a Cryogenic Wind Tunnel.** Paper no. 3 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. ONERA-TP-1982-89, 1982. 19 ...

A83-18427#

The thermal behavior of the structural elements of a cryogenic wind tunnel is examined along with the effects of thermal insulation on this behavior for the example of the planned European Transonic Windtunnel continuous-flow device. Time constants for responses to stepwise variations in gas temperature are calculated for elements located in the gas flow itself (screens and corner turning vanes), walls exposed to the gas flow on a single face, and elements only indirectly subjected to gas flow temperature variations (external walls and chamber supports). The wide range of time constants obtained is noted, and consequences for the thermal stresses of the structure are assessed. The attenuation of structural temperature variations by various types of internal insulation of the walls, which also allows more rapid changes in flow temperature and the reduction of energy consumption, is then considered. Possibilities for the thermal design of elements in the gas flow, the sting holder, test section walls and wind tunnel walls are presented.

*ONERA, BP 72, 92322 Chatillon Cedex, France

287 *Fuijkschot, P. H. **PEANUTS — The PETW Data System.** Paper no. 4 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. NLR Rept. MAW-82-009-U 14 pp.

N83-24519#

PEANUTS is centered around an HP-1000 computer system with 128 k words of RAM and 20 Mbyte of disc storage. The National Aerospace Laboratory (NLR) designed front end equipment includes a digital 10 bus interface, 16 low level channels using 'conditioning units', an operator control panel, a scanivalve controller, and a 50 channel relay scanner. For temperature measurements with type-T thermocouples a high precision unit with 60 Peltier cooled ice point reference junctions is available. The software for data acquisition is a proven NLR package with provisions for a monitoring loop and real time display of computed values. Measured data are stored in well defined files, while the subsequent processing is primarily the responsibility of TG-ETW (Technical Group-European Transonic Windtunnel).

*National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

288 *Graewe, E. **Development of a Cryogenic Windtunnel Balance.** Paper no. 5, pt. 1, at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. VFW Rept. KB-TE1-1173 25 pp.

N83-31611#

The behavior of bending beams from maraging steel equipped with strain gage bridges in the cryo-temperature-range is considered. Development of an unheated six component balance for the use in a cryogenic wind tunnel is considered.

*Vereinigte Flugtechnische Werke GmbH, Bremen, West Germany (FRG)

289 *Lorenz-Meyer, W. **Development of a Cryogenic Wind Tunnel Balance.** Paper no. 5, part 2, ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 17 pp.

N83-25722#

A six-component wind tunnel balance for cryogenic application was designed and constructed. A description is given of the design, instrumentation, and test setup.

*DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

290 *Schoenmakers, T. J. **Development of a Non-Insulated Cryogenic Strain-Gauge Balance.** Paper no. 6 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. NLR Rept. M-TP-82-006-U 26 pp.

N83-24520#

Measurement of aerodynamic forces in the European Transonic Windtunnel (ETW) is done with strain gage balances. The low and transient temperatures in this wind tunnel necessitate either keeping the balances at room temperature (heating and insulation) or developing special balances for cryogenic circumstances

(noninsulated). Experiments leading to the development of a three component cryogenic strain gage balance are reviewed and discussed briefly.

*National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

291 *Evans, J. Y. G.: **An Alternative Shape of Strain-Gauged Balance For Use in Wind Tunnels at Low-Temperatures.** Paper no. 7 ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 19 pp.

N83-33124#

The search for a shape of one-piece balance that might be more suitable than the conventional strain-gauge balance for general use in low-temperature wind tunnels led to a design with symmetry in both the pitch and yaw planes and with most of the drag stiffness concentrated at the axial location. Calculations of stress levels and deflection under load showed this design to have a performance similar to that of a modern conventional balance.

*Elven Precision Ltd., Crawley, U.K.

292 *Law, R. D.: **Early Experience In Using the Cryogenic Test Facility at RAE Bedford, England.** Paper no. 8 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 14 pp.

N83-25726#

A closed circuit test duct has been constructed at RAE Bedford as part of the United Kingdom support for the ETW program. The maximum gas velocity through the 0.3-m square test section is 25 m/sec, falling with temperature, and the gas temperature can be rapidly reduced and controlled at any level between ambient and 90 K by evaporation of liquid nitrogen. A simple calibration device is provided for loading small wind tunnel balances mounted in the test duct and some observations have been made of the behavior of a 3-component balance under transient temperature conditions.

*Royal Aircraft Establishment, Bedford MK41 6AE, U.K.

293 *Bald, W. B.: **Temperature Response of a Model to Set-Point Changes and Conditioning In ETW.** Paper no. 9 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 28 pp.

N83-25721#

Preliminary finite element thermal analysis of a model balance sting arrangement mounted in a cryogenic wind tunnel concluded that heated balances were unacceptable if the model surface temperature was to satisfy the 1 percent adiabatic wall temperature condition specified by Green. The results of a more detailed finite element thermal analysis on an assumed 0.6 meter long stainless steel delta wing model supported by an unheated balance sting arrangement and subjected to the ETW set-point changes and temperature conditioning specified are summarized.

*Dept. of Engineering Science, Parks Road, Oxford University, Oxford OX1 3PJ, U.K.

294 *Blanchard, A.; and *Mignosi, A.: **Problems Involved by the Instrumentation and the Conception of Cryogenic Tests.** Paper no. 10, at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 14 pp.

N83-25725#

The studies carried out on small pressure transducers tested at cool temperature and the development of a probe which was used in T'3 (a small cryogenic transonic wind tunnel driven with a fan) are presented. An important point concerns the precooling of the model, which is necessary in order to obtain a temperature ratio Tw/Taw near 1 during a run (20 to 40 seconds). This precooling is planned to be performed in a cooling box beside the test section, therefore, the model is introduced during the run starting process. To distinguish the effects due to the increase of Reynolds number, from those of specious conditions, the influence of various parameters must be discerned.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

295 *Paci, P.: **Practical Problems of Design and Manufacture of a 2-D Model and of the Device For Its Cooling and Introduction Into the T2 Pressurized Cryogenic Intermittent Tunnel.** Paper no. 11, at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. ONERA-TP-1982-88, 1982. 24 pp.

A83-14540#

A description is given of the design, fabrication, and operational problems which have been surmounted during the development of two-dimensional precooled models for use by the ONERA/CERT T2 cryogenic wind tunnel at Toulouse, France. The model must be at the tunnel airflow temperature from the outset of a cryogenic run, in order to avoid thermal exchanges through its skin. This cooling of the model is accomplished in a separate, model precooling box which is located to the side of the test section. A quick translation device integral with the precooling box is used to insert the model into the test section, where it is locked onto the incidence-determining apparatus and the desired pressure and speed are adjusted. Attention is given to the special design consideration given to the requirement for an 0.1-mm pressure tap diameter and the effects of thermomechanical deformations.

*ONERA, BP 72, 92322 Chatillon Cedex, France

296 *Schachterle, G., *Ludwieg, H., *Stanewsky, E.; and **Ray, E. J.: ***Design and Construction of Two Transonic Airfoil Models for Tests in the NASA Langley 0.3-m TCT.*** Paper no. 12 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. NASA TM-85325, 1982.

N83-23326#

As part of a NASA/DFVLR cooperation program two transonic airfoils were tested in the NASA Langley 0.3-m Transonic Cryogenic Tunnel. Model design and construction was carried out by DFVLR. The models designed and constructed performed extremely well under cryogenic conditions. Essentially no permanent changes in surface quality and geometric dimensions occurred during the tests. The aerodynamic results from the 0.3-m TCT tests, which demonstrate the large sensitivity of the airfoil CAST 10-2/DOA2 to Reynolds number changes, compared well with results from other facilities at ambient temperatures.

*DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

**NASA, Langley Research Center, Hampton, VA, 23665

297 *Zacharias, A.: **Parameter and Design Studies for the Use of Wind Tunnel Models in the ETW.** Paper no. 13 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. Rept. no. MBB/FE 123/S/PUB/83. 13 pp.

N83-24518#

The boundary conditions and the design criteria for cryogenic wind tunnel models were analyzed for a Tornado model in terms of their experimental and design problems. Some fundamental relationships concerning fluid mechanics for cryogenic wind tunnels, as

well as several experimental and model related considerations, were summarized as formulae

*Messerschmitt-Boelkow-Blohm GmbH, Munich, West Germany (FRG)

298 *Bazin, M. **Sting Line Feasibility for Force Measurements in the European Wind Tunnel.** Paper no. 14 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. ONERA-TP-1982-90, 1982. 20 pp.

A83-14541#

Apparent contradictions among published results concerning stagnation pressure limitations in model supports for the European Transonic Windtunnel (ETW) have prompted the present parametric analysis to ensure that the sting line mounting of the models and accurate force measurements will be possible at high pressure levels and transonic speeds. The modelling technique employed in the analysis uses base diameter and aspect ratio as parameters and makes possible a representation of numerous sting lines with two types of balances. The pressure limitations identified are due to balance capacities, strains, static divergence risk, and model base gap. These have been calculated for the cases of the Airbus airliner and Mirage 2000 fighter aircraft, at a scale that is well adapted to the ETW test section. A dimensional analysis makes possible the use of these results for every homothetical geometry.

*ONERA, BP 72, 92322 Chatillon Cedex, France

299 *Hoenlinger, H., and *Mussmann, D. **Some Aspects of Aeroelastic Models for Cryogenic Wind Tunnels.** Paper no. 16 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. Rept. no. MBB/FE294/S/PUB/80. 28 pp.

X83-74856 (NASA only)

*Messerschmitt-Boelkow-Blohm GmbH, Ottobrunn, West Germany (FRG)

300 *Schimanski, D.: **Investigations and Tests of Mechanisms for Wind Tunnel Models Under Cryogenic Test Conditions.** Paper no. 17 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. Rept. no. M/FE125/S/PUB/78 and DCAF F070087. 28 pp.

X83-74560 (U.S. Govt. agencies only)

*Messerschmitt-Boelkow-Blohm GmbH, Munich, West Germany (FRG)

301 *Petitniot, J. L., and *Dupriez, F. **Materials and Modelling Technology for Cryogenic Environment.** Paper no. 18 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 41 pp.

N83-25723#

Construction of a model and its support for use in a cryogenic wind tunnel induces the following problems relative to the choice of materials for the different model parts, lifting areas, fuselage, balance and sting line; construction techniques, depending on the aim of the tests to be done; joints between model and its support; joints between model support and wind tunnel structure; and isolated or non-isolated onboard instrumentation. According to type of tests, solicitations on the model in the test section will be very variable. For static tests, aimed at the determination of aerodynamic coefficients, maximum stress levels were fixed, with the agreement of air frame designers, to 400 MPa for civil and 800 MPa for fighter models. A dynamic stress is added to the static one whose value is of the order of 20 percent of the static stress. The frequency range lies beyond 30 to 50 Hz. As an example for a Mirage delta 2000 classic ⅛ scale model, first wing flexure mode is about 100 Hz. At this level, the balance stiffness effect becomes preponderant and the first frequencies met in the wind tunnel are those of the rigid modes of the model on its support.

*Institut de Mecanique des Fluides de Lille, 5 Bld. Paul PAINLEVE, 59000 Lille, France

302 *Luck, S. **Experimental Tests on Accelerometers and Pressure Transducers for Cryogenic Wind-Tunnel Models.** Paper no. 20 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. Rept. no. M/FE123/S/PUB/77. 22 pp.

N83-24517#

The function of accelerometers and pressure transducers in simulated conditions was shown, and demonstration of probes which might be used was given.

*Messerschmitt-Boelkow-Blohm GmbH, Munich, West Germany (FRG)

303 *Wagner, Bernhard. **Estimation of Simulation Errors in the European Transonic Windtunnel (ETW).** Paper no. 21 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 10 pp.

Note: For another presentation with the identical title and an abstract, see entry 283 in this bibliography.

*Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

This research was sponsored by the German Ministry of Research and Technology under support number LVW 7901 and by the Technical Group ETW, Amsterdam, under contract ETW/79/01/68730/143963.

304 *Dueker, M. **Condensation Studies in Cryogenic Nitrogen Expansions.** Paper no. 22 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 14 pp.

N83-25720#

The Reynolds number range of wind tunnels is extended to higher values when the wind tunnel operates under cryogenic conditions. With a stagnation temperature chosen too low, the gas may expand into its liquid or solid phase region, which will cause condensation effects. Avoiding impurities in the streaming medium, heterogeneous condensation is prevented, but in an isentropic expansion, far enough into the liquid or solid phase region, homogeneous condensation will occur. The determination of condensation onset points in isentropic expansions around realistic airfoils is tested in the European Transonic Windtunnel (ETW). Real gas effects in cryogenic flows are not described.

*DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

305 *Viehweger, G.: **The Cryogenic Wind Tunnel Cologne.** Paper no. 23 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982. 21 pp.

N83-25724#

The low speed wind tunnel in its original conception had a closed circuit and an open test section with a cross sectional area of about 7 m^2. After the cryogenic modification the tunnel has an internal insulation and a closed test section of 2.4 m × 2.4 m. The gas temperature is varied between 300 K and 100 K by injecting liquid nitrogen. The velocity is in the range of about 5 m/s to 100 m/s, depending on the actual temperature. By cooling down the

tunnel, the maximum Reynolds number is increased to more than 8 million.

*DFVLR Porz-Wahn, Postfach 90 60 58, 5000 Cologne 90, West Germany (FRG)

306 *Hall, R. M.; **Dotson, E. H.; and ***Vennemann, D. H. **Homogeneous and Heterogeneous Condensation of Nitrogen in Transonic Flow.** Paper no. 24 at the ETW Cryogenic Technology Review Meeting, NLR-Amsterdam, Sept. 15-17, 1982.

A82-43258#

For a previous presentation of this paper and an abstract, see entry 281 in this bibliography.

*NASA, Langley Research Center, Hampton, VA, 23665

**The George Washington University, NASA, Langley Research Center, Hampton, VA, 23665

***DFVLR Porz-Wahn, Postfach 90 60 58, 5000 Cologne 90, West Germany (FRG)

307 *Singh, J. J.; *Marple, C. G.; and *Davis, W. T.: **Characterization of Particles in the Langley 0.3-Meter Transonic Tunnel Using Hot Wire Anemometry.** NASA TM-84551, Sept. 1982. 18 pp.

N83-10407#

Hot wire anemometry was used to identify the nature of particles reportedly observed during free stream velocity measurements in the Langley 0.3-m Transonic Cryogenic Tunnel using a Laser Doppler Velocimeter. Since the heat-transfer process from the hot wire depends on the thermal conductivity and sticking capability of the particles, it was anticipated that the hot wire anemometer response would be affected differently upon impaction by liquid droplets and solid aerosols in the test gas stream. Based on the measured time response of the hot wire anemometer in the cryogenic tunnel operated in the 0.3-0.8 Mach number range, it is concluded that the particles impacting the hot wire are liquid in nature rather than solid aerosols. It is further surmised that the liquid aerosols are unevaporated liquid nitrogen droplets used for cooling the tunnel test gas.

*NASA, Langley Research Center, Hampton, VA, 23665

308 *Thibodeaux, Jerry J.: **Sensitivity Analysis of Cool-Down Strategies for a Transonic Cryogenic Wind Tunnel,** NASA TM-84527, Sept. 1982. 29 pp.

N83-10082#

Guidelines and suggestions substantiated by real-time simulation data to ensure optimum time and energy use of injected liquid nitrogen for cooling the Langley 0.3-m Transonic Cryogenic Tunnel (TCT) are presented. It is directed toward enabling operators and researchers to become cognizant of criteria for using the 0.3-m TCT in an energy- or time-efficient manner. The recommendations made herein, if followed, will result in minimum time and liquid-nitrogen usage during tunnel cool-down. These operational recommendations have been developed based on information collected from a validated simulator of the 0.3-m TCT and experimental data from the tunnel. Results and trends, however, can be extrapolated to other similarly constructed cryogenic wind tunnels.

*NASA, Langley Research Center, Hampton, VA, 23665

309 *Wigley, D. A.: **The Problem of Dimensional Instability in Airfoil Models for Cryogenic Wind Tunnels.** NASA CR-166003, Sept. 1982. 25 pp.

N83-13229#

The problem of dimensional instability in airfoil models for cryogenic wind tunnels is discussed in terms of the various mechanisms that can be responsible. The interrelationship between metallurgical structure and possible dimensional instability in cryogenic usage is discussed for those steel alloys of most interest for wind tunnel model construction at this time. Other basic mechanisms responsible for setting up residual stress systems are discussed, together with ways in which their magnitude may be reduced by various elevated or low temperature thermal cycles. A standard specimen configuration is proposed for use in experimental investigations into the effects of machining, heat treatment, and other variables that influence the dimensional stability of the materials of interest. A brief classification of various materials in terms of their metallurgical structure and susceptability to dimensional instability is presented.

*The University, Southampton SO9 5NH, Hampshire, U.K.

Contract NAS1-16000

310 *Leistner, Rudolf; *Zacharias, Athanasias; *Schimanski, Dieter; **Esch, Peter; **Joos, Roland; and **Thiel, Ernstfried: **Design and Manufacture of a Transonic Windtunnel Model and the Investigation of Model Components Under Cryogenic Flow Conditions in the European Transonic Windtunnel. Final Report, Sept., 1981.** Bundesministerium fuer Forschung und Technologie, BMFT-FB-W-82-015, Sept. 1982. 113 pp.

ISSN-0170-1339 N83-13078#

A Tornado model wing with high lift devices, which demonstrates that models which exhibit the critical aerodynamic characteristics for a design Reynolds number of 40 million can be built for the European Transonic Windtunnel, is presented. Stress, design life, safety factors, and mechanical and physical properties of design elements are discussed. Test data for maraging and austenitic steel elements are presented.

*Messerschmitt-Boelkow-Blohm GmbH, Munich, West Germany (FRG)

**Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

Sponsored by Bundesministerium fuer Forschung und Technologie (BMFT) Bonn, West Germany

311 *Webster, T. J.: **A Report on Possible Safety Hazards Associated With the Operation of the 0.3-m Transonic Cryogenic Tunnel at the NASA Langley Research Center.** NASA CR-166026, Oct. 1982. 11 pp.

N83-14140#

The Langley 0.3-m Transonic Cryogenic Tunnel (TCT) was built in 1973 as a facility intended to be used for no more than 60 hours in order to verify the validity of the cryogenic wind tunnel concept at transonic speeds. The role of the 0.3-m TCT has gradually changed until now, after over 3000 hours of operation, it is classified as a major NASA research facility and, under the administration of the Experimental Techniques Branch, it is used extensively for the testing of airfoils at high Reynolds numbers and for the development of various technologies related to the efficient operation and use of cryogenic wind tunnels. This report documents the results of a recent safety analysis of this facility. The analysis was made as part of an ongoing program within the Experimental Techniques Branch designed to ensure that the existing equipment and current oper-

ating procedures of the 0.3-m TCT facility are acceptable in terms of today's standards of safety for cryogenic systems

*Applied Cryogenics and Materials Consultants, Basin Road Industrial Center, P.O. Box 765, New Castle, DE 19720

NASA Order L-44921-B

312 *Burner, A. W., and *Goad, W. K. **Flow Visualization in a Cryogenic Wind Tunnel Using Holography.** NASA TM-84556, Nov. 1982. 22 pp.

N83-12395#

Results of holographic flow visualization are presented from tests made in the Langley 0.3-m Transonic Cryogenic Tunnel, which was operated over a temperature range from 100 to 300 K and a pressure range from 1.1 to 4.0 atm. Interferometry at the facility may be of limited use at the low-temperature — high-pressure conditions because of the jumbled nature of the reference fringes. The shadowgraph technique appears to be the best means of visualizing shocks at these high-density conditions. The spot size at the focus of the reconstructed beams was measured and used as an indicator of density fluctuations in the flow field. These density fluctuations appear to be caused by temperature fluctuations of the test gas which are relatively independent of tunnel conditions.

*NASA, Langley Research Center, Hampton, VA, 23665

313 *Snow, W. L., *Burner, A. W.; and *Goad, W. K. **Image Degradation in Langley 0.3-Meter Transonic Cryogenic Tunnel.** NASA TM-84550, Nov. 1982. 24 pp.

N83-13419#

The optical quality of gas in a cryogenic wind tunnel was determined by observing Sayce targets through different pathlengths of the medium. The data were used to determine the square wave response of the test gas. At conditions corresponding to 15 times ambient density, considerable decrease in response to higher spatial frequencies was noted even in the absence of flow. Under flow conditions, vibrations further degraded the response. The results are interpreted in terms of possible photogrammetric approaches to measure model deformation in large cryogenic facilities such as the National Transonic Facility.

*NASA, Langley Research Center, Hampton, VA, 23665

314 *Hoenlinger, Heinz, *Luck, Stephan; and *Schimanski, Dieter: **Basic Investigations for the Use of Wind Tunnel Models in the ETW. Final Report, Sept. 1981.** Bundesministerium fuer Forschung und Technologie, BMFT-FB-W-82-023, MBB/FE123/S/STY/0042. Dec. 1982. 49 pp.

ISSN-0170-1339 N83-24522#

The use of wind tunnel models at cryogenic temperatures places new demands on the equipment, instruments, and methods of construction applied hitherto. Their suitability is examined and recommendations are derived which should be observed in building and instrumenting wind tunnel models for cryogenic testing. In addition, methods are pointed out which allow, with some degree of convenience, an economical test procedure suited to the ETW. The report is divided into three main subjects.

(1) Instrumentation, (2) Mechanisms, and (3) Aeroelastic Models.

*Messerschmitt-Boelkow-Blohm GmbH, Ottobrunn, West Germany (FRG)

Sponsored by Bundesministerium fuer Forschung und Technologie

315 *Wagner, B.: **Boundary Layer Calculations for Cryogenic Wind Tunnel Flows.** Recent Contributions to Fluid Mechanics. Springer-Verlag, (Berlin), 1982. pp. 283-293.

A83-46478

The possible changes in the separation behavior of flows over airfoils in a cryogenic wind tunnel due to alterations in the wall temperature from thermodynamic gas effects and a slope change of the viscosity were investigated. Nitrogen was considered as the working fluid and attention was also given to nonadiabatic effects of walls without a predicted recovery temperature. The theoretical analysis was used to assess the effects of the wall temperature changes and the slope change on separation in high Re transonic flows. A boundary layer model was developed which takes the effects of the nonadiabatic and real gas effects into account. Changes in the wall temperature of up to 20 percent produced only negligible changes in the skin friction drag.

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Contracts BMFT-LVW-9901 and ETWT-79/01/68730/143963

316 *Japan Steel Works, Ltd. **9% Ni Steel.**** Brochure, 1982. 16 pp.

Contents: Specifications; manufacturing practice; internal quality; mechanical properties; susceptibility to temper embrittlement; fracture toughness; manufacturing experience, (1) hollow shaft forging, (2) disc forging, and (3) arc shape forging

*Japan Steel Works America, Inc., 200 Park Ave., New York, NY

**This brochure describes the production at Japan Steel Works, Ltd., of three of the major components of the U.S. National Transonic Facility (NTF), namely the drive shaft, the fan disc, and the angle-of-attack arc sector

317 *Hornung, H., *Hefer, G., *Krogmann, P., and *Stanewsky, E.: **Transonic Cryogenic Test Section for the Goettingen Tube Facility.** NASA TM-77050, Mar. 1983. Translation into English of German DFVLR Rept. no. IB-222-82A19, May 3, 1982. 19 pp.

N84-16219#

For abstract, see entry 273 in this bibliography.

*DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

318 *Esch, P.; and **Leistner, R.: **Studies Concerning Model Technology in the European Transonic Windtunnel (ETW).** Studien zur modell-technologie im ETW. Paper presented at Bundesministerium fur Forschung und Technologie, 3rd Status-seminar uber Luftfahrtforschung und Luftfahrttechnologie. Hamburg, West Germany, May 2-4, 1983. 42 pp. (In German.)

A83-47197#

Attention is given to a model design study to determine the feasibility of a simulation of the aerodynamic aircraft properties in the transonic velocity range under the cryogenic flow conditions of the ETW. The study is concerned with general configuration considerations for current and future aircraft and parameter and material studies. In addition, the practicality of simulation studies in the ETW is investigated for the military aircraft Tornado. A project description is provided, and test conditions in the ETW are discussed along with the model scale, the accuracy requirements, the characteristics of the employed models, recommendations for material selection, spe-

cial materials for flutter models, a cryogenic test chamber, the model mechanisms, and predesign work related to the Tornado model.

*Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

**Messerschmitt-Boelkow-Blohm GmbH, Munich, West Germany (FRG)

319 *Maurer, F. and *Viehweger, G. Statusbericht zum Europaischen Transschall Windkanal und zum Kryo-Kanal-Koln. **Status Report on the European Transonic Windtunnel and on the Cologne Cryotunnel.** Paper presented at Bundesministerium fur Forschung und Technologie, 3rd Statusseminar uber Luftfahrtforschung und Luftfahrttechnologie, Hamburg, West Germany, May 2-4, 1983. 42 pp. (In German.)

A83-47207#

Planned revisions of the design of the European Transonic Windtunnel are reported, emphasizing the planned enlargement of the tunnel and the financing of needed alterations. The revisions include the cancellation of an expensive pressure lock and possible alternatives involving compartmentalization of the measurement chamber. The possibility of supplementary internal insulation to deal with fatigue problems caused by fast variations in temperature is considered. The energy requirements of various phases of the project, the building costs, and the planned mean discharge plan are discussed.

*DFVLR Porz-Wahn, Postfach 90 60 58, 5000 Cologne 90, West Germany (FRG)

320 *Ewald, B. and **Graewe, E. Entwicklung einer 6-Komponenten-Waage fur den Kryo-Bereich. **Development of a Six-Component Weighing Device for Cryogenic Applications.** Paper presented at Bundesministerium fuer Forschung und Technologie, 3rd Statusseminar uber Luftfahrtforschung und Luftfahrttechnologie, Hamburg, West Germany, May 2-4, 1983. 33 pp. (In German.)

A83-47208#

The design and manufacture of an unheated 6-component balance for the model sting of a cryogenic wind tunnel are discussed. The application requires a compact device capable of bearing heavy loads and remaining accurate at temperatures from 90 to 320 K. The device constructed used electron-beam welded maraging steel for the body, type-WK wire strain gauges, and epoxy-resin glue and coating material. Materials testing at different temperatures and temperature gradients is summarized, drawings and photographs of the device are shown, and the design of the calibration shell is described. The errors in the measurement of axial forces which arose due to temperature gradients are corrected by means of software, which takes the measured temperature distribution in the device into account, thus accounting for even nonlinear effects.

*Darmstadt Technische Hochschule, Darmstadt, West Germany (FRG)

**Vereinigte Flugtechnische Werke GmbH, Bremen, West Germany (FRG)

321 *Gustafson, John C. **Control of Large Thermal Distortions in a Cryogenic Wind Tunnel.** JPL 17th Aerospace Mechanisms Symposium, May 1983, pp. 121-142

N83-24889#

The National Transonic Facility (NTF) is a research wind tunnel capable of operation at temperatures down to 78K (160°R) and pressures up to 880 kPa (8.8 atm) to achieve Reynolds numbers approaching 120 million. Wide temperature excursions combined with the precise alignment requirements of the tunnel aerodynamic surfaces imposed constraints on the mechanisms supporting the internal structures of the tunnel. The material selections suitable for this application were also limited. A general design philosophy of utilizing a single fixed point for each linear degree of freedom and guiding the expansion as required was adopted. These support systems allow thermal expansion to take place in a manner that minimizes the development of thermally induced stresses while maintaining structural alignment and resisting high aerodynamic loads. Typical of the support mechanisms are the preload brackets used in the fan shroud system and the Watts linkage used to support the upstream nacelle. The design of these mechanisms along with the basic design requirements and the constraints imposed by the tunnel system are discussed.

*NASA, Langley Research Center, Hampton, VA, 23665

322 *Lynch, F. T., *Fancher, M. F. and **Inger, G. R. **A Theoretical and Experimental Study of Non-Adiabatic Wall Effects on Transonic Shock/Boundary Layer Interaction.** Presented at the AIAA 18th Thermophysics Conference, Montreal, Canada, June 1-3, 1983. 40 pp.

AIAA Paper 83-1421 A83-34901#

Shock-boundary layer interaction can have a significant local and global influence on supercritical transonic viscous flow fields. Questions related to the alteration of interaction effects in connection with surface heat transfer processes are important in a number of contemporary aerodynamic problems, including the immersion of models in the low temperature nitrogen flow of a transonic cryogenic wind tunnel, cooled turbine blades in hot gas flows, the transonic supercritical flow field around the hot post-reentry Space Shuttle, and aerodynamic surface heating effects on the magnus moments acting on supercritical projectiles. A study conducted by Inger (1976) suggested that even moderate nonadiabatic wall effects could be practically significant in the applications. In the present investigation the problem is more extensively studied for a particular type of aerodynamic flow field. Attention is given to the two-dimensional nonseparating transonic flow on a nonadiabatic supercritical airfoil.

*Douglas Aircraft Co., McDonnell Douglas Corp., 3855 Lakewood Blvd., Long Beach, CA 90846

**West Virginia University, Morgantown, WV 26505

323 *Bald, W. B. **A Proposed Method for Model Temperature Conditioning in Cryogenic Wind Tunnels.** OUEL Rept. no. 1480/83, June 1983. 20 pp

N84-16224#

A technique for precooling models to any desired temperature for cryogenic wind tunnel tests is proposed. The model is placed in an insulated box with metal liner. Liquid nitrogen is pumped into the container until the temperature is -40°C. The cavity around the model is filled with Freon 12, giving a uniform model temperature of -30°C. The liquid nitrogen is connected to an internal cooling loop until the Freon 12 temperature near the bottom of the chamber reaches the desired level. No model distortion due to thermal stresses occurs.

*Dept. of Engineering Science, Parks Road, Oxford University, OX1 3PJ, U.K.

Contract Agreement no. 2057/072-XR/AFRO

324 *Dor, J. B.; *Mignosi, A.; and *Plazanet, M.: Qualification de la Soufflerie T2 en Fonctionnement Cryogenique. (A) Champ Thermique — Etude preliminaire d'une Maquette Schematique. **(Certification of the T2 Wind Tunnel During Cryogenic Operation. (A)**

Temperature Distribution — Preliminary Study of a Schematic Model.) *Rept DERAT no 24/5006 DN, Aug 1983. 112 pp* (In French).

This report presents some results from part of the certification tests of the T2 induction tunnel during cryogenic operation. Determination of the transverse temperature distribution in the tunnel under cryogenic test conditions is discussed. Methods and instrumentation used are described.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

325 *Hunter, W. W., Jr., *Honaker, W. C. and *Gartrell, L. R.: **Application of Laser Anemometry to Cryogenic Wind Tunnels.** International Congress on Instrumentation in Aerospace Simulation Facilities, ICIASF '83, Saint-Louis, Haut-Rhin, France, Sept. 20, 1983, pp. 200-208.

A84-25226#

The installation and tests conducted with the laser Doppler and transit anemometer in the Langley 0.3-m Transonic Cryogenic Tunnel are described. Using residual particulates in the flow field, a series of free stream velocity measurements were conducted which agreed to within 1 percent of predicted values for a range of Mach numbers, 0.2 to 0.85, and temperatures, 100 to 250 K. Measurements about a shock wave provided an estimate of scattering particulate size of 4 microns or less. The particle concentration is approximately 3×10^5 to 1.6×10^6 per m^3. Necessary isolation of the plenum wall windows from ambient air with slightly positive pressure of dry nitrogen gas to prevent condensation on the window surface was achieved. This was accomplished through the use of large enclosures fixed to the tunnel wall. A second method used an additional sheet of thin plate glass to create the dry gas pocket next to the plenum window. The installation of a laser anemometer in the National Transonic Facility is examined. The laser transit anemometer has been tentatively selected for the initial entry because of its compact laser-optics package.

*NASA, Langley Research Center, Hampton, VA, 23665

326 *AGARD: **Wind Tunnels and Testing Techniques.** AGARD-CP-348, Fluid Dynamics Panel Symposium on Wind Tunnels and Testing Techniques, Cesme, Turkey, Sept. 26-29, 1983, 514 pp.

ISBN-92-835-0348-1 N84-23564#

The design and operation of cryogenic wind tunnels and transonic facilities are discussed as well as associated fluid motion problems. Testing techniques are considered with emphasis on support interference, inlet/engine/afterbodies, store separation, half models, aeroacoustic measurements, and wind tunnel-flight data comparisons.

*AGARD, 7 Rue Ancelle, 92200 Neuilly-sur-Seine, France

Note: Thirty-six papers are contained in this volume. Papers pertinent to cryogenic wind tunnels are listed separately below.

327 *McKinney, L. W.: **Operational Experience With the National Transonic Facility.** Paper no. 1 in AGARD-CP-348, Wind Tunnels and Testing Techniques, a symposium held at Cesme, Turkey, Sept. 26-29, 1983. 8 pp.

N84-23565#

Construction of the National Transonic Facility was completed in September 1982. The checkout of all systems required about 1 year. The facility operated to the design point of 120 million Reynolds number based on a 0.25-m chord at a Mach number of 1.0. Performance of all systems was basically as expected. Setup for the detailed aerodynamic calibration begins late in 1983, and the calibration is expected to be complete by the last quarter of 1984.

*NASA, Langley Research Center, Hampton, VA, 23665

328 *North, R. J., *Maurer, F., *Prieur, J., *Schimanski, D., and Tizard, J. A.: **The European Transonic Windtunnel (ETW) — Status Report.** Paper no. 2 in AGARD-CP-348, Wind Tunnels and Testing Techniques, a symposium held at Cesme, Turkey, Sept. 26-29, 1983. 12 pp.

N84-23566#

The status of the preliminary design phase of the European Transonic Windtunnel project is described. The latest version of the proposed tunnel is given together with some details of its estimated performance. Some features of the tunnel which were revised following the first preliminary design proposals are discussed and the results of an investigation into the expected future use of the tunnel are summarized. An aerodynamic circuit test rig is described along with some of the results obtained. Information on the pilot tunnel is included as well as reference to the supporting program on cryogenic technology.

*Technical Group, ETW, National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

329 *Mignosi, A., and *Dor, J. B.: La Soufflerie Cryogenique a Parois Auto-Adaptables T2 de l'ONERA/CERT. **The ONERA/CERT T2 Cryogenic Wind Tunnel With Self-Adaptable Walls.** Paper no. 3 in AGARD-CP-348, Wind Tunnels and Testing Techniques, a symposium held at Cesme, Turkey, Sept. 26-29, 1983. 12 pp. ONERA-TP-1983-117, 1983. 17 pp. (In French.)

A84-23567#
A84-13630#

The transonic induction driven wind tunnel T2 at the ONERA Toulouse Research Center is equipped with a 0.4 m×0.4 m test section and is a pressurized closed circuit wind tunnel, operating at ambient temperature with runs of 30 to 60 seconds. The wind tunnel was adapted for cryogenic operation using liquid nitrogen as a coolant and an internal thermal insulation. The main characteristics of the wind tunnel at low temperature and of the constituents used to perform airfoil tests with adaptive walls are described. The flow qualities are analyzed through an evaluation of the thermal gradients, pressure and thermal fluctuations studies, and the operating limit at very low temperature. The effects of various parameters able to influence test results are examined, such as boundary layer transition and differences between wall temperature and adiabatic wall recovery temperature.

*ONERA/CERT, BP 4025 31055 Toulouse Cedex, France

330 Viehweger, G.: **The Cryogenic Wind Tunnel Cologne.** Paper no. 4 in AGARD-CP-348, Wind Tunnels and Testing Techniques, a symposium held at Cesme, Turkey, Sept. 26-29, 1983. 8 pp.

N84-23568#

The modification of a low-speed wind tunnel to cryogenic operation is discussed. The tunnel, with a test section of 2.4 m×2.4 m, should be operational in the middle of 1984. The technical concept of the tunnel is examined and some of the most important components are described.

*DFVLR Porz-Wahn, Postfach 90 60 58, 5000 Cologne 90, West Germany (FRG)

331 *Chauvet, Dominique; and **Dujarric, Christian: Production d'une Rafale Cryogenique dans une Soufflerie de Type Eiffel Atmospherique a Rafale Courte. **Producing a Cryogenic Gust in an**

Eiffel Type Atmospheric Wind Tunnel With Short Gust. Paper no 5 in AGARD CP-348, Wind Tunnels and Testing Techniques, a symposium held at Cesme, Turkey, Sept 26-29, 1983 17 pp (In French)

N84-23569#

Demonstrations of the feasibility of an Eiffel-type cryogenic atmospheric wind tunnel with short gusts and of the economy of operation of such a concept requires prior resolution of certain specific technical problems found in this type wind tunnel. The technique for generating cryogenic gaseous flow by atomizing liquid nitrogen in air at the level of the plenum chamber is described as well as the chronological feeding out of a cryogenic gust. Theoretical and experimental studies are developed for optimizing the evaporation of liquid nitrogen in the plenum chamber of a wind tunnel. The results of measuring the grain size of drops of liquid nitrogen are compared with a computation model which correctly represents the real behavior of the aerosol.

*Institut Aerotechnique de Saint-Cyr, 15 rue Marat, 78210 Saint-Cyr-l'Ecole, France

**Service Technique des Programmes Aeronautiques, 4 avenue de la Porte d'Issy, 75015 Paris, France

332 *Wagner, Bernhard, and *Doker, Michael: **Prediction of Condensation Onset and Growth in the European Transonic Windtunnel (ETW).** Paper no 13 in AGARD-CP-348, Wind Tunnels and Testing Techniques, a symposium held at Cesme, Turkey, Sept 26-29, 1983 11 pp

N84-23578#

Experimental and theoretical investigations were carried out to allow reliable prediction of condensation onset and growth in cryogenic wind tunnels. The idea of streamline duplication was used in the experiments in order to simulate European Transonic Windtunnel (ETW) streamlines in an experimental facility of small cross section but with real ETW length scale. Classical nucleation theory was used for developing computer programs which can predict condensation processes in one-dimensional flow including real gas effects. Experiments and calculations show satisfactory agreement and confirm the possibility of an operating range extension for the ETW. The results provide some new data with respect to those cases where the condensate consists of solid particles.

*Dornier GmbH, Postfach 1420, D-7990 Friedrichshafen 1, West Germany (FRG)

**DFVLR, Bunsenstrasse 10, D-3400 Goettingen, West Germany (FRG)

333 *Lynch, F. T., *Fancher, M. F., *Patel, D. R., and **Inger, G. R. **Nonadiabatic Model Wall Effects on Transonic Airfoil Performance in a Cryogenic Wind Tunnel.** Paper no. 14 in AGARD-CP-348, Wind Tunnels and Testing Techniques, a symposium held at Cesme, Turkey, Sept 26-29, 1983, 11 pp.

N84-23579#

The need to match the aircraft surface thermal conditions that exist at in-flight conditions when testing models in a cryogenic wind tunnel is addressed. Effects of nonrepresentative heat transfer are reviewed for such basic viscous characteristics as the effect on boundary-layer transition location, the effects on turbulent boundary-layer integral parameters and skin friction, the effect on the transonic turbulent boundary-layer-shock-wave interaction, and the effects on separation onset and the extent of separated flow regions. A complementary experimental and computational investigation was conducted in order to help quantify the impact that nonadiabatic model wall conditions would have on the measured aerodynamic characteristics of transport (and other) airplane configurations tested in a cryogenic wind tunnel, and to help establish the allowable deviation from adiabatic wall conditions that can be tolerated if reliable results are to be obtained. Test results are presented which illustrate the large impact of moderate amounts of heat transfer on the lift and drag characteristics for both free-transition flow in the absence of any shock waves and for typical cruise conditions with moderate strength shocks on the airfoil. In addition, test results are shown which illustrate a very large effect of heat transfer on buffet onset conditions and conditions near maximum lift.

*Douglas Aircraft Co., McDonnell Douglas Corp., 3855 Lakewood Blvd., Long Beach, CA 90846

**West Virginia University, Morgantown, WV 26505

334 *Griffin, Stanley A., *McClain, A. A., and **Madsen, A. P. **Design of Advanced Technology Manuevering Aircraft Models for the National Transonic Facility.** Paper no. 25 in AGARD-CP-348, Wind Tunnels and Testing Techniques, a symposium held at Cesme, Turkey, Sept 26-29, 1983, 15 pp.

N84-23590#

The need for a large high-Reynolds-number transonic wind tunnel which will provide a tool to study phenomena sensitive to Reynolds number is discussed. The National Transonic Facility (NTF) is in the calibration phase and has the desired capability. Its usefulness, however, will be influenced by the ability of industry to develop model systems capable of withstanding the severe operating environment of the facility so necessary to achieve full-scale Reynolds number without degradation of accuracy and at reasonable cost. The feasibility of designing models of advanced aerodynamic technology maneuvering aircraft and to achieve full scale Reynolds number for each configuration in the NTF are determined. It is concluded that the facility does offer the potential for making tunnel to full scale data correlations for this type of aircraft configuration.

*General Dynamics, Corp., Convair Division P.O. Box 85377, San Diego, CA, 92138

**General Dynamics Corp., Fort Worth Division, P.O. Box 748, Fort Worth, TX, 76101

335 *Dotson, Edward H. **Homogeneous Nucleation and Droplet Growth in Nitrogen.** M.S. Thesis, George Washington University, Joint Institute for Advancement of Flight Sciences, Sept. 1983, NASA CR-172206 88 pp

N83-34231#

A one-dimensional computer model of the homogeneous nucleation process and growth of condensate for nitrogen flows over airfoils is developed to predict the onset of condensation and thus to be able to take advantage of as much of Reynolds number capability of cryogenic tunnels as possible. Homogenous nucleation data have been taken using a DFVLR CAST-10 airfoil in the Langley 0.3-m Transonic Cryogenic Tunnel and are used to evaluate the classical liquid droplet theory and several proposed corrections to it. For predicting liquid nitrogen condensation effects, use of the arbitrary Tolman constant of 0.25×10^{-10}m or the Reiss or Kikuchi correction agrees with the CAST-10 data. Because no solid nitrogen condensation had been found experimentally during the CAST-10 experiments, earlier nozzle data are used to evaluate corrections to the classical liquid droplet theory in the lower temperature regime. A theoretical expression for the surface tension of solid nitrogen is developed.

*The George Washington University, NASA, Langley Research Center, Hampton, VA, 23665
Cooperative Agreement NCC1-44

336 *Tripp, John S.: **Development of a Distributed-Parameter Mathematical Model for Simulation of Cryogenic Wind Tunnels.** NASA TP-2177, Sept. 1983. 50 pp.

N83-35736#

A one-dimensional distributed-parameter dynamic model of a cryogenic wind tunnel has been developed which accounts for internal and external heat transfer, viscous momentum losses, and slotted-test-section dynamics. Boundary conditions imposed by liquid-nitrogen injection, gas venting, and the tunnel fan have been included. A time-dependent numerical solution to the resultant set of partial differential equations has been obtained on a CDC CYBER 203 vector-processing digital computer at a usable computational rate. Preliminary computational studies were performed by using parameters of the Langley 0.3-m Transonic Cryogenic Tunnel. Studies have been performed by using parameters from the National Transonic Facility (NTF). The NTF wind-tunnel model has been used in the design of control loops for Mach number, total temperature, and total pressure and for determining interactions between the control loops. It has been employed in the application of optimal linear-regulator theory and eigenvalue-placement techniques to develop Mach number control laws.

*NASA, Langley Research Center, Hampton, VA, 23665

337 *Dor, Jean-Bernard; *Mignosi, Andre; and *Plazanet, Michel: (A). Qualification de la Soufflerie T2 en Fonctionement Cryogenique. (B). Fluctuations de l'Ecoulement—Detection et Qualification de Particlues. **(A). Certification of the T2 Wind Tunnel During Cryogenic Operation. (B). Fluctuations in the Flow—Detection of Particles in Cryogenic Flow and Apparatus Used for a Qualitative Study.)** Rept. DERAT no. 25/5006 DN, Sept. 1983. 81 pp. (In French.)

Some results are presented of the certification tests of the T2 transonic induction tunnel during its operation at cryogenic temperatures. The first part gives results concerning pressure and temperature in both ambient and cryogenic regimes. The second part shows the phenomena of condensation in cryogenic flow using an optical system of detecting particles.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

338 *Departmente d'Etudes et de Recherches en Aerothermodynamique (D.E.R.A.T.): Recherches Effectuees au D.E.R.A.T. (Octobre 1982 a Septembre 1983) Bilan des Principaux Resultats Acquis. **(Research at D.E.R.A.T., Summary of Principal Results Obtained.)** Paper presented at the meeting of the Conseil d'Orientation (Guidance Council), Oct. 17, 1983. 49 pp. (In French.)

The two areas of activity discussed are (1) fundamental studies in viscous and turbulent flow, and (2) experimental methods of testing in subsonic-transonic flow. Pages 32-41 discuss the adaptation of the T2 tunnel for cryogenic operation and tests of the CAST-7 airfoil. A description of the T3 cryogenic tunnel is then given.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

339 *Mignosi, A.: **Cryogenic Methods in Wind Tunnels.** Paper presented at the Association Aeronautique et Astronautique de France, 20th Colloque d'Aerodynamique Appliquee, Toulouse, France, Nov. 8-10, 1983. 31 pp. (In French.)

AAAF Paper NT 83-08 A84-32479

Current progress in the application of low-temperature techniques to achieve flightlike Reynolds numbers in wind tunnels is surveyed. The basic principles of cryogenic wind tunnel operation and the associated boundary layer, transition, flow quality, and condensation limit problems are reviewed. The technology and instrumentation employed in the various facilities (NTF, ETW, KKK, T2, PETW) are discussed and illustrated with diagrams.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

340 *Kilgore, R. A.; *Dress, D. A., and *Lawing, P. L.: **Some of the Capabilties and Desirable Features of an "Ideal" Transonic Wind Tunnel.** NASA TM-85484, Nov. 1983. 23 pp.

N84-72329

Personnel of the Experimental Techniques Branch were asked to make a contribution to the definition of an "ideal" transonic tunnel in a survey being conducted under the auspices of the Ground Testing Technical Committee of the American Institute of Aeronautics and Astronautics (AIAA). The purpose of this paper is to document the response of the Branch to that survey. Based on a large number of conflicting requirements, the "consensus ideal" transonic tunnel would have a 2.5 m×2.5 m test section, operate at pressures from about 0.5 to 5.0 atm, temperatures from about 77.4 to 340 K, and cover the range of Mach numbers from about 0.02 to 1.30. The maximum Reynolds number at sonic speeds would be about 5 million based on a reference dimension of 0.25 m. Desirable features would include a water-air heat exchanger for ambient temperature operation, an adjustable second minimum, an adaptive-wall test section (solid walls), and a magnetic suspension and balance system.

*NASA, Langley Research Center, Hampton, VA, 23665

341 *Nelander, Curt: **A Quasi-Continuous Transonic Wind Tunnel for Cryogenic Operation.** ROLLAB-Memo-RM-096, Nov. 1983. 13 pp.

N84-15161#

An alternative for driving a transonic or subsonic facility of medium to large size is described. The principle is to drive the fan in a closed circuit tunnel by using an air turbine fed by a high-pressure air storage. The temperature rise imposed by the fan will be taken care of by introducing the cold outlet air from the turbine into the tunnel circuit. The same amount of air will be dumped to the atmosphere via a heat exchanger or matrix, thus cooling down the high pressure air. The stagnation enthalpy in the tunnel will be the same as the enthalpy of the driving gas in front of the turbine and the regeneration of the matrix accomplished by the temperature difference due to the Joule-Thomson effect.

*Aktiebolaget Rollab, Jarvstigen 5, Box 7073, S-17107 Solna, Sweden

342 *Portat, M.; and *Helias, F.: **Characterization of Pressure Transducers for Future Cryogenic Wind Tunnels.** In ESA-TT-841, English edition of La Recherche Aerospatiale, Bimonthly Bulletin no. 1983-6, Nov.-Dec., 1983, pp. 35-40.

N84-25873#

Operating cryogenic wind tunnels will require measurement equipment adapted to the specific environmental conditions. Among other things, it must be known how the existing wind tunnel pressure transducers will behave in a cryogenic environment. To this end, ONERA has developed special instruments to measure pressure transducer characteristics accurately between 300 and 120 K. Static tests carried out on the Kulite XCQL and ONERA 20H130 transducers show that they are usable at 120 K.

*ONERA, BP 72, 92322 Chatillon Cedex, France

343 *Boyden, Richmond P.; *Johnson, William G., Jr.; and *Ferris, Alice T.: **Aerodynamic Force Measurements With a Strain-**

Gage Balance in a Cryogenic Wind Tunnel. NASA TP-2251, Dec. 1983. 42 pp.

N84-13162#

Aerodynamic force measurements on a generalized 75° delta-wing model with sharp leading edges have been made with a three-component internal strain-gage balance in a cryogenic wind tunnel at stagnation temperatures of 300, 200 and 110 K. The feasibility of using a strain-gage balance without thermal control in a cryogenic environment as well as the use of electrical resistance heaters, an insulator between the model and the balance, and a convection shield on the balance was investigated. Force and moment data on the delta-wing model as measured by the balance are compared at the different temperatures while holding constant either the Reynolds number or the tunnel stagnation pressure. Tests were made at Mach numbers of 0.3 and 0.5 and at angles of attack up to 29°. The results indicate that it is feasible to acquire accurate force and moment data while operating at steady-state thermal conditions in a cryogenic wind tunnel, either with or without electrical heaters on the balance. Within the limits of the balance accuracy, there were no apparent Reynolds number effects on the aerodynamic results for the delta-wing model.

*NASA, Langley Research Center, Hampton, VA, 23665

344 *Klich, P. J.; and *Cockrell, C. E.: **Mechanical Properties of a Fiberglass Prepreg System at Cryogenic and Other Temperatures.** AIAA Journal, vol. 21, Dec. 1983, pp. 1722-1728. Presented at the AIAA/ASME/ASCE/AHS 23rd Structures, Structural Dynamics, and Materials Conference, New Orleans, La., May 10-12, 1982.

AIAA Paper 82-0708 A84-13580#

The test results given in this paper provide mechanical and physical properties of an epoxy E-glass system at cryogenic and elevated temperatures. E-glass cloth pre-impregnated with an epoxy resin was selected as the material for the fan blades in NASA's new cryogenic wind tunnel, the National Transonic Facility (NTF). Because of the limited data available on E-glass at cryogenic temperatures, a comprehensive testing program was undertaken at the Langley Research Center to develop a data base to support the design of the NTF fan blades. The fan blades were constructed of 7781 and 7576 style E-glass cloths with EF-2 resin. Tests were conducted that completely characterize the strength and elastic properties of laminates made of each of the cloths, as well as of a laminate representative of the fan blade construction, at cryogenic, room, and elevated temperatures. In addition,to these tests, creep, fatigue, and thermal expansion tests were conducted.

*NASA, Langley Research Center, Hampton, VA, 23665

345 *Schoenmakers, T. J.; and *Baljeu, J. F.: **Development of a Non-Insulated Cryogenic Strain-Gauge Balance. Estimate of the Accuracy of Balance No. 771 at Temperatures Between 90 K and 300 K.** NLR-National Aerospace Lab, Amsterdam, TP-82-005-U, 1983. 9 pp.

N83-26045#

The influence of the combination of loads acting on it, the temperature, and the temperature gradients on a three component cryogenic balance was investigated. The effect of combined loads is determined at room temperature and is taken into account by means of a second order calibration. The temperature effects give rise to the application of four corrections on the test data. The estimated accuracy of the cryogenic balance presented is the summation of the accuracy with which the corrections were determined. The measurement of aerodynamic drag appears to be considerably less accurate than the measurement of the lift and pitching moment, mainly due to the influence of temperature gradients.

*National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

346 *Hall, R. M.: **Pre-Existing Seed Particles and the Onset of Condensation in Cryogenic Wind Tunnels.** Presented at the AIAA 22nd Aerospace Sciences Meeting, Reno, Nevada, Jan. 9-12, 1984. 9 pp.

AIAA Paper 84-0244 A84-17972#

The condensation research at NASA Langley Research Center has used a variety of experimental approaches to gather information on seed particles that can act as sites for condensation growth. Total pressure measurements have suggested that condensation growth is caused by impurities in the flow and not by unevaporated liquid nitrogen (LN_2) injected to cool the 0.3-m Transonic Cryogenic Tunnel. A separate test with an optical droplet sizing probe, which was designed to detect droplets in the 2- to 300- m range, confirmed the conclusions from the total pressure measurements and also discovered what appears to be solidified oil droplets having diameters of about 3 m. These oil droplets appear to be the dominant source of seed particles above 2 m. However, computer simulations of static pressure test data suggest that the measured condensation effects are the result of more numerous, smaller seeds with number densities on the order of 10^{12} per kilogram of the gas and diameters on the order of 0.5 m.

*NASA, Langley Research Center, Hampton, VA, 23665

347 *Hartzuiker, J. P.: **The European Transonic Windtunnel ETW: A Cryogenic Solution.** Main Society Lecture of The Royal Aeronautical Society, Jan. 25, 1984. Published in the Aeronautical Journal, Nov. 1984 pp. 379-394.

A85-17240

The Governments of France, the Federal Republic of Germany, The Netherlands, and the United Kingdom are co-operating under a Memorandum of Understanding to build a transonic wind tunnel for high Reynolds numbers. This lecture presents the history of the project and the specification and performance of ETW. The expected mode of operation of the facilities described and the design features, peculiar to this wind tunnel, are summarized. A short description is given of PETW, of a test rig for aerodynamic measurements, and of the supporting programs on model design and instrumentation. Finally, the siting of ETW and the time schedule up till operation are addressed.

*National Aerospace Laboratory, Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands

348 **AIAA 13th Aerodynamic Testing Conference — Technical Papers,** San Diego, CA, March 5-7, 1984. 346 pp.

A84-24176

Various topics on aerodynamic testing are addressed. the subjects considered include: aeropropulsion systems test facility; real-time engine testing; transport configuration wind tunnel test with engine simulation, civil turbofan propulsion system integration studies using powered testing techniques; dynamic measurements in the settling chamber of a transonic cryogenic tunnel; aerodynamic and propulsion test unit with vitiated air heater, and subscale testing of an ice suppression system for Space Shuttle launches. Also discussed are: dynamic flow quality measurements in a low-turbulence pressure tunnel; data acquisition and reduction techniques for a solar collector pressure test; application of adaptive wall to high-lift subsonic aerodynamic testing; wind tunnel tests on a high-performance low-Reynolds number airfoil; development and cali-

bration of miniature Mach-flow-angularity probes; pressure records analysis in an unsteady expansion wave; and a new concept for exhaust diffusers of altitude test cells.

Note: Several papers of possible interest to the users of this bibliography are listed separately as follows.

349 *Bruce, W. E., Jr.; *Fuller, D. E.; and *Igoe, W. B.: **National Transonic Facility Shakedown Test Results and Calibration Plan.** Presented at the AIAA 13th Aerodynamic Testing Conference — Technical Papers, San Diego, CA, Mar. 5-7, 1984. 13 pp

AIAA Paper 84-0584 A85-16101#

The construction of the National Transonic Facility was completed in September 1982, and shakedown operations started the following month, with the maximum Reynolds number being obtained in May 1983. Since then, most of the effort has been devoted to installing the model access housings and adjusting or altering various tunnel components. The current ongoing effort is devoted to checkout of the model attitude, plenum isolation, and model access systems. Upon completion of this, the aerodynamic calibration will follow. The facility has been operated in both air and nitrogen modes covering a Mach number range of 0.2 to 1.17 at pressures up to 8.5 atm and at temperatures down to 100 K. A limited amount of performance information was obtained during shakedown and is presented in this paper, along with an outline of the calibration plans for the tunnel.

*NASA, Langley Research Center, Hampton, VA, 23665

350 *Gloss, B. B.: **Initial Research Program for the National Transonic Facility.** Presented at the AIAA 13th Aerodynamic Testing Conference — Technical Papers, San Diego, CA, Mar. 5-7, 1984, pp. 1-11

AIAA Paper 84-0585 A84-24177#

The construction and checkout of the National Transonic Facility (NTF) have been completed, and detailed calibration is now in progress. The initial NTF research program covers a wide range of study areas falling into three major elements: (1) The assessment of Reynolds number sensitivities for a broad range of configurations and flow phenomena; (2) validation of the ability of NTF to simulate full-scale aerodynamics; and (3) the development of test techniques for improved test simulations in existing wind tunnels. This paper, therefore, is a status report on these various elements of the initial NTF research program.

*NASA, Langley Research Center, Hampton, VA, 23665

351 *Young, C. P., Jr.; *Bradshaw, J. F.; *Rush, H. F., Jr.; *Wallace, J. W., and *Watkins, V. E., Jr.: **Cryogenic Wind-Tunnel Model Technology Development Activities at the NASA Langley Research Center.** AIAA 13th Aerodynamic Testing Conference —Technical Papers, San Diego, CA, Mar. 5-7, 1984. pp. 12-29.

AIAA Paper 84-0586 A84-24178#

This paper summarizes the current cryogenic wind-tunnel model technology development activities at the NASA Langley Research Center. These research and development activities are being conducted in support of the design and fabrication of models for the new National Transonic Facility (NTF). The scope and current status of major research and development work is described and, where available, data are presented from various investigations conducted to date. In addition, design and fabrication experience for existing developmental models to be tested in the NTF is discussed.

*NASA, Langley Research Center, Hampton, VA 23665

352 *Johnson, C. B.; and *Stainback, P. C.: **A Study of Dynamic Measurements Made in the Settling Chamber of the Langley 0.3-m Transonic Cryogenic Tunnel.** AIAA 13th Aerodynamic Testing Conference — Technical Papers, San Diego, CA, Mar. 5-7, 1984. pp. 109-119.

AIAA Paper 84-0596 A84-24186#

Tests have been conducted in a cryogenic wind tunnel settling chamber using fast response instrumentation to measure the possible existence of temperature fronts due to a sudden or step change in the rate of liquid nitrogen injection into the circuit. No indications of such fronts were obtained using three different techniques to change the rate of nitrogen injection. The normalized pressure and velocity fluctuations at two total temperatures and over a large range of Mach numbers and Reynolds numbers were about 2×10^{-7} to 2×10^{-4} and about 1.8 to 3 percent, respectively. There was no evidence of liquid nitrogen droplets in the flow down to a total temperature of 140 K. The pressure fluctuation power spectra from a pressure transducer correlated with the fan blade passage through the eighth harmonic of the fundamental frequency.

*NASA, Langley Research Center, Hampton, VA, 23665

353 *Christophe, J.; *Bazin, M.; *Broussaud, P.; *Francois, G., *Paci, P.; and *Dubois, M.: **Developments In Research Stimulated By Cryogenic Wind Tunnel Construction Planning and Projects.** La Recherche Aerospatiale (English edition), no. 2, Mar.-Apr., 1984, pp. 25-44.

ISSN-0379-380X A84-46764#

Recent developments in cryogenic wind tunnel research are briefly summarized. Particular emphasis is given to work currently being performed by ONERA in the effort to design transonic wind tunnels with high Reynolds numbers. Some technical considerations in the design of the European Transonic Windtunnel are discussed, including wind tunnel insulation, the use of alternative gases such as nitrogen, and the properties of materials to be used in the construction of wind tunnel models. Consideration is also given to the design and construction of precooling and wind tunnel introduction devices.

*ONERA, BP 72, 92322 Chatillon Cedex, France

354 *Michel, R.; and *Mignosi, A.: **First Cryogenic Tests of an Airfoil in ONERA/CERT T2 Wind Tunnel.** La Recherche Aerospatiale (English edition), no. 2, Mar.-Apr. 1984, pp. 69-71.

ISSN-0379-380X A84-46767

The adaptation of the transonic T2 induction-driven wind tunnel at an ONERA research center for operation at low temperatures has required internal thermal insulation through the entire circuit; and to cool the flow, a liquid nitrogen injection device has been installed. Before entering the operational phase of studies on models in cryogenic flow, the cryogenic operation of the wind tunnel was maximized through the study of the establishment and stabilization of temperature, the qualification of flow qualities, and the preparation of a preliminary operation to cool the models. Currents studies involve tests of a CAST 7 airfoil subjected to different pressures and temperatures, and the determination of its aerodynamic characteristics through a range of Reynolds numbers. Two aspects are presented for the test technique: use of a gaseous nitrogen cooling device, and the use of adpative walls which are formed to simulate boundary conditions very close to those of an infinite flow field. An initial cryogenic test program has been run on the CAST 7 airfoil, some results used to confirm temperature test validity conditions are presented, and a definition of the coefficient of lift variation with the Reynolds number is obtained.

*ONERA, BP 72, 92322 Chatillon Cedex, France

355 *Germain, Edward F.; and *Compton, E. Conrad: **Evaluation Tests of Platinum Resistance Thermometers for a Cryogenic Wind Tunnel Application.** NASA TM-85803, Apr. 1984. 16 pp.

N84-23865#

Thirty-one commercially designed platinum resistance thermometers were evaluated for applicability to stagnation temperature measurements between -190°C and 65°C in the U.S. National Transonic Facility. Evaluation tests included X-ray shadowgraphs, calibrations before and after aging, and time constant measurements. Two wire-wound low-thermal-mass probes of a conventional design were chosen as most suitable for this cryogenic wind tunnel application.

*NASA, Langley Research Center, Hampton, VA, 23665

356 *Daryabeigi, K., and *Ash, R. L.: **NTF Stagnation Temperature Measurement. Final Report, 1 June 1983–15 January 1984.** NASA CR-173380, April 1984. 39 pp.

N84-73576

The accuracy of the National Transonic Facility (NTF) stagnation temperature measurement system was investigated. Issues addressed included the accuracy of a simplified calibration approximation of the 1968 International Practical Temperature Scale for platinum resistance thermometers (employed in this system), and the accuracy of the supporting instrumentation. In addition, the conduction error for the platinum resistance thermometer configuration used in the NTF was investigated. This analysis shows that the NTF stagnation temperature measurement system can be accurate to within ±0.06 K over the interval 126.15 K $\leq$ T $\leq$ 363.15 K.

*Old Dominion University, Norfolk, VA, 23508

NASA Grant NAS1-17099

357 *Kilgore, Robert A.: **Cryogenic Wind Tunnels for High Reynolds Number Testing.** Lecture presented at the University of Tennessee Space Institute Short Course on Aerospace Ground Test Facilities and Flight Testing, Tullahoma, Tennessee, May 8, 1984. 63 pp. (An enlarged, updated version of previous presentations.)

A84-42900#

This lecture is intended to provide an overview of the evolution and early development of cryogenic wind tunnels, a status report on some of the cryogenic wind tunnel activities around the world, and, finally, a brief look at some developments aimed at further improving the testing capabilities of wind tunnels.

*NASA, Langley Research Center, Hampton, VA, 23665

358 *Carlson, A. B.: **Thermal Analysis of Cryogenic Wind Tunnel Models.** AIAA 19th Thermophysics Conference, Snowmass, CO, June 25-28, 1984. 9 pp.

AIAA Paper 84-1802 A84-37516#

This paper summarizes the thermal analysis activity being performed in support of the design of wind tunnel models for the National Transonic Facility (NTF) at the NASA Langley Research Center. The goal of the analysis effort has been to address model design difficulties associated with the severe thermal environment of this cryogenic wind tunnel. The unique characteristics of this environment are discussed for various phases of tunnel operation. The methods used to calculate temperatures and thermal stresses in the models are also described. The results indicate that thermal considerations do not drive the design to the extent originally envisioned. In general, the problems identified are localized and associated with thermal mismatch between components. Several specific examples of thermal design problems and proposed solutions are given.

*NASA, Langley Research Center, Hampton, VA, 23665

359 *Graewe, E.: **Development of a 6-Component Balance for the Cryogenic Range. Final Report, April 1983.** DCAF E002631. Rept. no. BMFT-IB-W-84-022, June 1984. 51 pp.

ISSN-0170-1339 N84-30270#

Criteria for wind tunnel strain gage component balances applicable in the temperature range 100 to 300 K were derived. An unheated six-component balance was constructed and examined. With the corresponding software this balance is practicable on quasi stationary temperatures in the range 100 to 300 K.

*Messerschmitt-Boelkow-Blohm GmbH, Bremen, West Germany (FRG)

360 *Campbell, James F.: **The National Transonic Facility — A Research Perspective.** Paper presented at the AIAA 2nd Applied Aerodynamics Conference, Seattle, Wash., Aug. 21-23, 1984. 17 pp.

AIAA Paper 84-2150 A84-44189#

The status of the calibration, correlation, and research efforts of the National Transonic Facility (NTF) is presented. The research program is reviewed in more detail, citing aerodynamic problem areas and research needs and the accompanying NTF program which addresses some of these needs. The description of the research program is broken into four categories: Basic Fluid Mechanics, Transport Aircraft Aerodynamics, Fighter Aircraft Aerodynamics, and Computational Fluid Dynamics.

*NASA, Langley Research Center, Hampton, VA, 23665

361 *Goodyer, M. J.: **Engineering Changes to the 0.1 m Cryogenic Wind Tunnel at Southampton University.** NASA CR-172430, Aug. 1984. 20 pp.

N84-32397

This report outlines the more important changes to the tunnel since its completion in 1977. These include detailed improvements in the fan drive to allow higher speeds and the provision for a test section leg suitable for use with a magnetic suspension and balance system. The instrumentation, data logging, data reduction, and tunnel controls have also been improved and modernized. The report concludes with a tunnel performance summary.

*The University, Southampton SO9 5NH, Hampshire, U.K.

Contract NAS1-16000

362 *Wallace, John W.: **Fastener Load Tests and Retention Systems Tests for Cryogenic Wind-Tunnel Models.** NASA TM-85805, Aug. 1984. 46 pp.

N84-28964#

This paper presents the results of a fastener load and retention systems test program, which was carried out as a part of the cryogenic models technology development activities at the NASA Langley Research Center. A-286 stainless steel screws were tested to determine the tensile load capability and failure mode of various screw sizes and types at both cryogenic and room temperatures. Additionally, five fastener retention systems were tested by using A-286 screws with specimens made from the primary metallic alloys that are currently used for cryogenic models. The locking-system effectiveness was examined by simple no-load cycling to cryogenic temperatures (-275°F) as well as by dynamic and static loading at cryogenic temperatures. In general, most systems were found to be effective retention devices. There are some differences between the

various devices with respect to ease of application, cleanup, and reuse. Also, results of tests at -275°F imply that the cold temperatures act to improve screw retention. The improved retention is probably the result of differential thermal contraction and/or increased friction (thread-binding effects). The data in this paper are provided for use in selecting screw sizes, types, and locking devices for model systems to be tested in cryogenic wind tunnels.

*NASA, Langley Research Center, Hampton, VA, 23665

363 *Kilgore, R. A.; and *Dress, D. A.: **The Application of Cryogenics to High Reynolds Number Testing in Wind Tunnels. Part 1: Evolution, Theory, and Advantages.** Cryogenics, vol. 24, no. 8, Aug. 1984, pp. 395-402.

ISSN-0011-2275

An improved way to increase the Reynolds number capability of wind tunnels has been developed in the United States at the NASA Langley Research Center through the application of cryogenic technology. Cooling the test gas in the wind tunnel to cryogenic temperatures by spraying liquid nitrogen into the tunnel circuit increases the test Reynolds number by as much as a factor of 7 with no increase in dynamic pressure and with a reduction in drive power. Part 1 of this two-part review covers the evolution, theory, and major advantages of cryogenic wind tunnels. Part 2 will describe the development and early application of the cryogenic wind tunnel concept in the United States and some of the major cryogenic wind tunnel activities around the world, the most significant of which is a large fan-driven transonic cryogenic tunnel recently completed at the Langley Research Center.

*NASA, Langley Research Center, Hampton, VA, 23665

364 *Kilgore, R. A.; and *Dress, D. A.: **The Application of Cryogenics to High Reynolds Number Testing in Wind Tunnels. Part 2: Development and Application of the Cryogenic Wind Tunnel Concept.** Cryogenics, vol. 24, no. 9, Sept. 1984, pp. 484-493.

ISSN-0011-2275

An improved way to increase the Reynolds number capability of wind tunnels has been developed through the application of cryogenic technology. Part 1 of this two-part review covered the evolution, theory, and major advantages of cryogenic wind tunnels. This paper describes the development and early application of the cryogenic wind tunnel concept in the United States at the NASA Langley Research Center. Also presented are some of the major activities around the world related to cryogenic wind tunnels, the most significant of which is a large transonic cryogenic tunnel recently completed at the Langley Research Center.

*NASA, Langley Research Center, Hampton, VA, 23665

365 *Lawing, Pierce L.; *Dress, David A.; and *Kilgore, Robert A.: **Description of the Insulation System for the 0.3-m Transonic Cryogenic Tunnel.** NASA TM-86274, Jan. 1985.

The thermal insulation system of the 0.3-m Transonic Cryogenic Tunnel (TCT) at the NASA Langley Research Center is described in text, photographs, and drawings. The system is designed to operate from room temperature down to about 77.4 K, the temperature of liquid nitrogen at 1 atm. A detailed description is given of the primary insulation system, which consists of glass fiber mats, a 3-part vapor barrier, and a dry nitrogen positive-pressure purge system. Also described are several secondary insulation systems required for the test section, actuators, and tunnel supports. An appendix briefly describes the original insulation system which is considered inferior to the one presently in place. The time required for opening and closing portions of the insulation system for modification or repair to the tunnel has been reduced, typically, from a few days for the original thermal insulating system to a few hours for the present system.

*NASA, Langley Research Center, Hampton, VA, 23665

366 *[illegible], J.: and *Dor, J.B.: **Estimating Heat Losses and Calculating Flow Characteristics in an Intermittent Cryogenic Wind Tunnel.** (Estimation des pertes thermiques et calculs des caracteristiques de l'encoulement dans une soufflerie à rafales cryogeniques.) ONERA-CERT R.T. DCAF F[illegible]0143, June 1978, 44 pp. In French.

N84-75683

The first part of the report describes the phenomenon of heat transmission in different parts of the aerodynamic circuit of the T'2 wind tunnel. The second part develops the equations which describe the flow in this cryogenic wind tunnel.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

367 *Green, J.D.; and *Taylor, C.R: **Enhancement of the ETW Operating Envelope by Increasing Maximum Pressure and Power.** RAE-TM Aero 1827, Dec. 1979, 29 pp.

Langley Library number CN-154941

This memorandum considers the potential for improving the ability of the European Transonic Windtunnel (ETW) to simulate full-scale flight conditions, for a relatively modest increase in cost, by increasing the strength of the pressure shell and slightly augmenting the power of the main drive relative to the values required to meet the AGARD LaWs specification. The question of increasing the size of the tunnel, in order to meet the LaWs requirements at a reduced pressure, is also addressed. This memorandum has been prepared by RAE, with the assistance from the ETW Technical Group in defining tunnel performance parameters, as a contribution to final discussions of the tunnel specification.

*Royal Aircraft Establishment, Farnborough, Hampshire GU14 6TD, U.K.

368 *Gobert, J.L.: and *Breil, J.F.: **Preliminary Study of an Apparatus to Control the Temperature of the Flow Entering the T2 Cryogenic Wind Tunnel.** (Etude preliminaire d'un dispostif de controle de la temperature de l'ecoulement destine a la soufflerie cryogenique T2). ONERA-CERT R.T. OA 20/5007, April 1983, 37 pp.

The use of intermittent cryogenic wind tunnels has necessitated the control of the parameters of the flow temperature, pressure, and speed. This report gives the results of a preliminary study done in the CERT T'2 wind tunnel. The feasibility of a temperature control apparatus which uses a real time mini-computer is shown.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex, France

369 *Mignosi, A: and *Imbert, R.: **First Cryogenic Test of the CAST 7 Profile in the T2 Wind Tunnel. Comparison with Calculations.** (Premiers essais cryogeniques du profil CAST 7 à la soufflerie T2. Comparaisons avec les calculs.) (ONERA-RTS-58/1685-AY-035-D), April 1984, 66 pp. In French.

N85-13682#

The influence of Reynolds number at a Mach number of 0.76 was studied in natural and enhanced transition using a CAST 7 airfoil profile with 150 mm chord. The wind tunnel and the experimental technique are described. Studies on wall choice and on the thermal equilibrium of the model are included. Computations solving the transonic potential equation with inclusion of viscous effects are presented. Important differences between experiment and theory are observed.

*ONERA, BP 72, 92322 Chatillon Cedex, France
Contract DRET-83-34-135.

370 *Elsenaar, A.: **Technical Evaluation Report on the Fluid Dynamics Panel Symposium on Wind Tunnels and Testing Techniques.** AGARD-AR-193, May 1984, 13 pp. Symposium held in Cesme, Turkey, Sept. 26-29, 1983.

ISBN-92-835-1473-4 N84-32402#

Testing techniques and wind tunnels were discussed. New facilities and their performance, design, wind tunnel tests like scale effects and disturbance effect were reported. New developments in cryogenic testing techniques, and refinement of conventional techniques, instrumentation, model design and construction are reported. The increasing impact of computer development on wind tunnel testing is addressed.

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371 *Beck, J.W.: **Cryogenic Wind Tunnel Technology - A Way to Measurement at Higher Reynolds Numbers.** NASA-TM-77481, May 1984, 34 pp. Translation from "Kryo-Windkanal-Technologie: Ein Weg zur Messung bei Hoeheren Reynolds-Zahlen," Munich, Feb. 1, 1982, pp. 53-81, 83-87, A83-46484.

N84-34451#

The goals, design, problems, and value of cryogenic transonic wind tunnels being developed in Europe are discussed. The disadvantages inherent in low-Reynolds number (Re) wind tunnel simulations of aircraft flight at high Re are reviewed, and the cryogenic tunnel is shown to be the most practical method to achieve high Re. The design proposed for the European Transonic Windtunnel (ETW) is presented: parameters include test section = 4 sq m, operating pressure = 5 bar, temperature = 110 to 120 K, maximum Re = 40 million, liquid N2 consumption = 40,000 metric tons/year, and power = 39.5 MW. The Cologne subsonic tunnel being adapted to cryogenic use for preliminary studies is described. Problems of configuration, materials, and liquid N2 evaporation and handling and the research under way to solve them are outlined. The benefits to be gained by the construction of these costly installations are seen more in applied aerodynamics than in basic research in fluid physics. The need for parallel development of both high Re tunnels and computers capable of performing high-Re numerical analysis is stressed.

Note: See no. 258 in this bibilography for original German form.

*DFVLR, Oberpfaffenhofen, West Germany

372 *Pan Ruikang: **A Cryogenic High-Reynolds Number Transonic Wind Tunnel with Pre-Cooled and Restricted Flow. Acta Aerodynamica Sinica** (China Aerodynamics Research Society) No. 2, 1984, pp. 87-92. In Chinese.

In order to achieve the full scale Reynolds number of aircraft in model testing, various high-Reynolds number transonic wind tunnels are being developed abroad. In this paper, a cryogenic high-Reynolds number transonic wind tunnel with pre-cooled and restricted flows is presented. The principle that air temperature falls down through a flow restrictor, which is also a regulator, is applied. Air from a compressor is first cooled to 215 K, and then enters into the pressure vessels. During the wind tunnel operation, the regulating valve must be controlled, so that fluid pressure is 5 atm and its temperature is 154 K. Under the different Mach number condition, the different temperature and pressure may be used to achieve a Reynolds number as high as 16.7×10^7. In this paper, the cool-system of the wind tunnel and the tunnel operating principles are described in detail, as well as the 2.4 m transonic wind tunnel scheme.

*China Aerodynamic Research and Development Center (CARDC), P.O. Box 211, Mianyang, Sichuan, China

373 *Griffin, S.A.; **Madsen, A.P.; and M. Lain, A.A.: **Design Study of Test Models of Maneuvering Aircraft Configurations for the National Transonic Facility (NTF).** NASA-CR-3827, Aug. 1984, 283 pp.

N84-33422#

The feasibility of designing advanced technology, highly maneuverable, fighter aircraft models to achieve full scale Reynolds number in the U.S. National Transonic Facility (NTF) is examined. Each of the selected configurations are tested for aeroelastic effects through the use of force and pressure data. A review of materials and material processes is also included.

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P.O. Box 748, Forth Worth, TX 76101

Contract NAS1-16848

374 *Department d'Etudes et de Recherches en Aerothermodynanique (D.E.R.A.T.): Recherches Effectuées au D.E.R.A.T., (Oct. 1983 - Sept. 1984) Bilan des Principaux Résultats Acquis. **(Research at D.E.R.A.T., (Oct. 1983 - Sept. 1984) Summary of Principal Results Obtained.)** Paper presented at the meeting of the Conseil d'Orientation (Guidance Council). Oct. 20, 1984, 41 pp. In French.

Discussed are: (A) Fundamental studies of viscous and turbulent flows, and (B) Experimental methods and tests in subsonic-transonic flow. Some specific topics addressed are: wing-fuselage interference, boundary-layer transition, calculation of 3-dimensional boundary-layers, tests in the T2 cryogenic wind tunnel on adaptive walls and other corrections for wall interference, tests on the CAST 7 airfoil, problems related to the use of cryogenic tunnels, instruments for them such as friction gauges and the cryogenic wind tunnel balance for the T2.

*ONERA/CERT, BP 4025, 31055 Toulouse Cedex,
France

375 *Hartzuiker, J.P.: **The European Transonic Windtunnel ETW: A Cryogenic Solution.** "The Aeronautical Journal," Nov. 1984, pp. 379-394.

A85-17240

Note: For an earlier form of this paper and an abstract, see no. 347 in this bibliography.

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376 *ONERA, Centre d'Etudes et de Recherches de Toulouse, France: **Research Done at **D.E.R.A.T. (October 1982 Through September 1983); Summary of Principal Results Obtained.** NASA-TM-77786, Dec. 1984, 79 pp. An English translation of a French report dated Oct. 17, 1983, pp. 1-42.

N85-17730#

Note: See no. 338 in this bibliography for the original French form.

The progress in the following areas is described: measurement equipment, F2 FAUGA wind tunnel tests, unsteady boundary-layers, body and axisymmetrical boundary-layers, wing fuselage interactions, turbulence, and subsonic-transonic flow. The adaptation of the T2 tunnel for cryogenic operation and tests of the CAST 7 airfoil are discussed and a description of the T'3 cryogenic tunnel is given.

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France

**Department of Studies and Research in
Aerothermodynamics

377 Morisset, J.: **ETW, the European Cryogenic Windtunnel Will Be Built in Cologne, West Germany. (ETW, soufflerie cryogénique européenne sera construite en Allemagne à Cologne).** Air et Cosmos, vol. 22, Dec. 15, 1984, pp. 24, 25. In French.

ISSN 0044-6971 A85-18723

It is expected that an intergovernmental agreement will soon be completed to produce a final design for the ETW, which has been under study since 1978. The project will be one of cooperation among the United Kingdom, West Germany, The Netherlands, and France. Costing an estimated 1.4 billion francs, the facility will allow studies of Mach 0.9 flows at Re up to 50 million, i.e., just over that experienced by the Airbus 300. The wind tunnel will have a 2.4 x 2 m test section, operate at pressures from 1.25 - 4.5 bars and at temperatures from -183 to +40 °C, and will furnish flows of Mach 0.15 - 1.3 with nitrogen as the test gas. The fan will be driven by a 45 MW motor and the tunnel will be 120 m long. A smaller, pilot ETW has recently entered service in Amsterdam.

378 Morisset, J.: **The Most Spectacular Equipment - ETW.** Air et Cosmos, vol. 22, Dec. 22, 1984, pp. 55-57. In French.

A85-[illegible]

The European Transonic Windtunnel (ETW) will be built in the next 10 years as a cooperative effort of four countries and will serve for tests of fixed wing aircraft, helicopters, and missiles. Preliminary design work for the ETW, which will be constructed in Cologne-Porz, began in 1977. The final design features a 2.4 x 2 m test section, a -183 to + 40 °C temperature range, a 1.25 to 4.5 atm pressure range, Mach numbers from 0.15 to 1.3, a maximum Re of 50 million, and a 61,000 hp blower. A cryogenic pressurized mode was chosen to faithfully reproduce flight conditions with sub-scale models, which will be supported on a dynamic mobile balance equipped with a sting. The cryogenic flow will be produced by injecting liquid nitrogen into the tunnel circuit at rates up to 200 kg/sec. A smaller version of the ETW, known as the PETW, was completed in the spring of 1984 in Amsterdam and is serving as a pilot for operational techniques for the ETW.

379 *Hall, R.M.: **Studies of Condensation *Effects on Airfoil Testing in a Transonic* Cryogenic Tunnel.** AIAA 23rd Aerospace Sciences Meeting, Reno, Nevada, Jan. 14-17, 1985, 12 pp.

AIAA Paper 85-0229 A85-19630#

The results of condensation studies in the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT) utilizing the NACA 0012-64, NPL 9510, NACA 0012, NASA 0712-3, and CAST 10-2/DOA 2 airfoils are summarized as follows: (1) the value of maximum local Mach number over the airfoil, $M_{\ell,max}$, is the most important correlation parameter for the data, (2) both homogeneous nucleation and condensation on pre-existing seed particles occurred, depending on the value of $M_{\ell,max}$, (3) a curve fit to an analytic study by Sivier does a good job of correlating the data, (4) a simple procedure is documented to predict minimum operating temperatures in the 0.3-m TCT, (5) increases in Reynolds number capability of up to 22 percent are predicted because of the ability to test below local saturation before the onset of condensation effects, (6) at values of M_∞ below 0.55, effects may occur above local saturation if operating tunnel pressures are low, and (7) airfoil surface pressure measurements appear to be as sensitive to condensation as drag rake data.

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380 *Cole, S.R.: **Exploratory Flutter Test in a Cryogenic Wind Tunnel.** *AIAA/ASME/ASCE/AHS 26th Structures, Structural Dynamics and Materials Conference*, Orlando, Florida, April 15-16, 1985, 9 pp.

AIAA Paper 85-0736

An experimental study to explore the feasibility of conducting flutter tests in cryogenic wind tunnels was conducted in the NASA LaRC 0.3-m Transonic Cryogenic Tunnel (TCT). The model used consisted of a rigid wing with an integral, flexible beam support that was cantilever mounted from the tunnel wall. The wing had a rectangular planform of aspect ratio 1.5 and a 64A010 airfoil. Various considerations and procedures for conducting flutter tests in a cryogenic wind tunnel were evaluated. Flutter onset conditions were established from extrapolated subcritical response measurements. A flutter boundary was determined at cryogenic temperatures over a range of Mach number, M, from 0.5 to 0.9. Flutter was obtained at two different Reynolds numbers, R, at M = 0.5 (R = 4.4 and 18.4 x 10^6) and M = 0.8 (R = 5.0 and 10.4 x 10^6). The approach used in this study was to design a flutter model that would be both simple to analyze and reasonably safe to test in a cryogenic wind tunnel. A reliable analytical prediction of the flutter boundary was important so that actual "hard" flutter could be avoided during the test, or, at least, approached cautiously. Even so, this test was approached as a high-risk test in the 0.3-m TCT.

*NASA Langley Research Center, Hampton, VA 23665

381 *Adachi, T.; *Matsuuchi, K.; **Matsuda, S.; and *Kawai, T.: **On the Force and Vortex Shedding on a Circular Cylinder from Subcritical up to Transcritical Reynolds Numbers.** Bulletin of the JSME (In English), vol. 28, no. 243, 1985.

Pressure distribution and vortex shedding were measured in the 0.5 x 0.5 m low-speed cryogenic wind tunnel at Tsukuba from subcritical up to transcritical Reynolds numbers ($10^5 \leq Re \leq 10^7$) and Mach numbers up to 0.3 without changing the experimental arrangement. A brief description the tunnel and its operating characteristics are given. Drag coefficients were calculated using pressure distributions. Pressure distributions and drag coefficients show characteristic changes for subcritical, lower transition, critical, upper transition and transcritical Reynolds number ranges, respectively. Strouhal number takes constant value with an increase in Reynolds number for $10^5 \leq Re \leq 3.2 \times 10^5$. Narrow-band vortex shedding could not be measured in the critical Reynolds number range ($3.2 \times 10^5 \leq Re \leq 6.9 \times 10^5$). It was also measured again in the upper transition and transcritical Reynolds number ranges. Spectra of the pressure distributions and velocity fluctuations measured are presented for several characteristic values of Reynolds numbers. Results are also compared with those of the other authors.

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APPENDIX
GENERAL CRYOGENIC PUBLICATIONS

The following entries, while not dealing directly with cryogenic wind tunnels, have been found to be useful sources of information.

A1 *Corruccini, Robert J., and *Gniewek, John J.: **Specific Heats and Enthalpies of Technical Solids at Low Temperatures—A Compilation From the Literature.** NBS Monograph 21, Oct. 1960.

N63-81125

Tables are given of the specific heat, c_p, and the enthalpy of 28 metals, 3 alloys, 8 other inorganic substances, and 8 organic substances in the temperature range 1 to 300 K.

*National Bureau of Standards, Boulder, CO, 80302

A2 *Jacobs, R. B.: **Liquid Requirements for the Cool-Down of Cryogenic Equipment.** Advances in Cryogenic Engineering, Vol. 8, 1963, pp. 529-535. Presented at the Cryogenic Engineering Conference, Los Angeles, Calif., Aug. 1962.

It is frequently necessary to estimate the amounts of cryogenic liquid required to cool cryogenic equipment to its operating condition. The purpose of this paper is three-fold: (1) to derive relations for making these estimates; (2) to compute the cool-down requirements for the commonly used liquids (helium, hydrogen, nitrogen, and oxygen) with some commonly used materials (stainless steel, copper, and aluminum); and (3) to present the results of the computations in a readily usable graphical form.

*National Bureau of Standards, Boulder, CO, 80302

A3 Pankhurst, R. C.; and Holder, D. W.: **Wind Tunnel Technique.** Sir Isaac Pitman and Sons, Ltd., London, 1965.

This book is an attempt to satisfy the need which the authors felt to exist for a coherent account of modern wind-tunnel practice written in the form of a critical resume rather than as a textbook which starts from first principles. It is intended primarily for graduates entering the field of experimental aerodynamics since it is felt that, although having a good knowledge of the theory, they may in many cases have had little opportunity of becoming familiar with experimental practice. It is hoped that the work may also be of value as a reference book for the research worker and for the model-testing personnel of aircraft firms. The scope of the book is best judged from the Contents and from the forward references to the remainder of the text given in Chapter 1. For this reprint (1965) we have been able to correct known misprints and other errors (particularly the omission of the chord/span ratio from equations (3)-(5) on p. 238) but have not introduced fresh material. The only substantial alteration occurs in Chapter VIII, where the drag correction ascribed to wall-induced inclination of the lift vector has been deleted in cases of two-dimensional flow.

A4 Barron, Randall F.: **Cryogenic Systems.** McGraw-Hill, New York, 1966. (McGraw-Hill series in mechanical engineering).

The objective of this book is to present an introduction to the engineering aspects and challenges of cryogenics. Emphasis is placed on the design and analysis of systems used to produce, maintain, and utilize low temperatures. The text is an outgrowth of class notes and lecture material associated with a course in cryogenic systems taught at Ohio State University and is slanted primarily toward senior mechanical engineering students, although the text is arranged so that it may be used by an engineer unfamiliar with cryogenic techniques when he is called upon to assist in the design of a system for low temperatures. The required background for the student includes a knowledge of the basic engineering sciences—thermodynamics, heat transfer, fluid flow, and mechanics of solids. Because a book must always have a finite number of pages, not all topics in cryogenics are covered, but it is hoped that a student will have a firm foundation in cryogenics after studying this text. The text is intended for a one-semester undergraduate course in cryogenic systems. Books for additional reading are suggested at the end of each chapter.

A5 *Scurlock, R. G.: **Low Temperature Behaviour of Solids: An Introduction.** Routledge and Kegan Paul, Ltd., London. Dover Publications, Inc., New York, 1966.

This book provides an elementary introduction to the behaviour of solids, at temperatures ranging down from room temperature. It is directed at the level of the second or third year undergraduate student in science and engineering, and provides a concise account of some of the more important properties of the solid state. A strict mathematical approach is avoided, and discussion is limited to qualitative, order of magnitude, explanations of low temperature behaviour.

*University of Southampton, SO9 5NH, Southampton, U.K.

A6 *Wigley, D. A.: **Mechanical Properties of Materials at Low Temperatures.** Plenum Press, New York-London, 1971. 377 pp.

A72-19909

The aim has been to consider the mechanical properties of the wide range of materials now available in such a way as to start with the fundamental nature of these properties and to follow the discussion through to the point at which the reader is able to comprehend the significance or otherwise of the large amounts of data now available in design manuals and other compilations. In short, it is hoped that this volume will be used as a companion to these data compilations and as an aid to their interpretation. Most of the materials likely to be of use in cryogenic engineering have been included but, despite the superiority of nonmetals for certain applications, it is a reflection of the major importance of metals that about 70 percent of the book is devoted to their deformation and fracture characteristics.

*The University, Southampton SO9 5NH, Hampshire, U.K.

A7 *Reed, William E.: **Cryogenic Refrigeration, Vol. 2. A Bibliography With Abstracts.** Progress Rep., 1973-Oct. 1977, NTIS/PS-78/1261/3, Dec. 1978. 236 pp.

N79-16144#

Cryogenic cooling of electronic equipment, infrared equipment cryogenic storage vessels, magnetohydrodynamic generators, and superconducting magnets, coils, rotating machinery, and transmission lines is reported. Marine refrigeration of liquefied natural gas, cryogenic heat pipes, cryogenic heat transfer, and space applications are studied. Methods investigated include adiabatic demagnetization, electrocaloric effect, Joule-Thompson effect, thermoelectric cooling, and Crayton, Claude, Gifford-McMahon, Sterling, and Vuilleumier cycles. This updated bibliography contains 229 abstracts, none of which are new entries to the previous edition.

*National Technical Information Service, 5285 Port Royal Road, Springfield, VA, 22161

A8 *Reed, William E.: **Cryogenic Refrigeration, Vol. 3. A Bibliography With Abstracts.** Progress Rep., Nov. 1977-Nov. 1978. 84 pp.

N79-16145#

Cryogenic cooling of electronic equipment, infrared equipment cryogenic storage vessels, magnetohydrodynamic generators, and superconducting magnets, coils, rotating machinery, and transmission lines is reported. Marine refrigeration of liquefied natural gas, cryogenic heat pipes, cryogenic heat transfer, and space applications are studied. Methods investigated include adiabatic demagnetization, electrocaloric effect, Joule-Thomson effect, thermoelectric cooling, and Crayton, Claude, Gifford-McMahon, Sterling, and Vuilleumier cycles. This updated bibliography contains 77 abstracts, all of which are new entries to the previous edition.

*National Technical Information Service, 5285 Port Royal Road, Springfield, VA, 22161

A9 *Wigley, D. A. **Materials for Low-Temperature Use.** *Engineering Design Guide, no. 26*, Design Council, Oxford Univ. Press, London, England, 1978. 37 pp.

N83-78254

Includes the effect of temperature on the strength, toughness, and basic failure mechanisms in metals. Also includes the influence of cracks and flaws—fracture toughness and time-dependent failure. Discusses the effect of temperature on the mechanical properties of non-metals and the effect of temperature on the physical properties of metals and non-metals.

*Applied Cryogenics and Materials Consultants, Basin Road Industrial Center, P.O. Box 765, New Castle, DE, 19720

A10 *Webster, T. J. **Latest Developments in Cryogenic Safety.** Presented at 9th International Cryogenic Engineering Conference (ICEC9), Kobe, Japan, May 11-14, 1982. NASA CR-166087, Mar. 1983. 15 pp.

A82-46474#
N83-36276#

Some general aspects of cryogenic safety are highlighted, and attention is drawn to some of the more unusual hazardous situations. An awareness of the physical properties of the cryogenic fluids being dealt with is important in directing attention to hazardous situations which may arise. Because of this, the more important properties of the cryogenic fluids are given, such as molecular weight, boiling point, and freezing point. From these properties, hazardous situations can be deduced. There are hidden dangers that are not always easy to spot. Some of the unexpected hazards, most of which have led to deaths, are: asphyxiation (anoxia), frostbite and hypothermia, explosions, and combustion. The aim of this publication is to help bring about increased safety in the production and use of cryogenic products through a deeper appreciation of the scientific, technological and administrative steps which must be made if accidents, some fatal, are to be avoided in the future.

*Applied Cryogenics and Materials Consultants, Basin Road Industrial Center, P.O. Box 765, New Castle, DE, 19720

A11 British Cryogenics Council: **Cryogenics Safety Manual—A Guide to Good Practice, Second edition.** Mechanical Engineering Publications, Ltd., London, 1982. 115 pp.

TP482.B7, 1982

This manual constitutes a revision of the original *Cryogenics Safety Manual* published in 1970. It is aimed at those who are engaged in the production, handling, and use of cryogenic fluids, whether on a large scale in industry or on a small scale in research.

The manual consists of five parts, the first of which is concerned with general safety requirements relating to all the cryogenic fluids and explains the hazards to health and the general precautions necessary in handling. The remaining four parts deal with specific fluids, in groups or individually. Thus, Part II is concerned with oxygen, nitrogen, and argon, while Part III deals with liquefied natural gas, ethylene, and ethane. Part III also contains nine Hazard Data Sheets, describing the particular hazards associated with methane, ethylene, ethane, propylene, refrigerant 22, benzene, hydrogen sulphide, butane, and propane. Part IV is concerned with the particular problems of handling hydrogen, and Part V deals with the inert gases helium and neon.

The revision has been undertaken by a working group of the British Cryogenics Council, bearing in mind the need for improved safety training and the continuing development and improvement of safety techniques and equipment. Experience has shown that all cryogenic fluids can be handled safely, provided certain precautions are observed; it is the purpose of this revised *Cryogenics Safety Manual* to focus attention on the basic precautions which are necessary.

Appendix C

Transcript of Discussions

This appendix contains a near verbatim transcription of announcements, discussions, and comments made during the AGARD-FDP VKI Special Course *Cryogenic Technology for Wind Tunnel Testing* held at the von Karman Institute, April 22-26, 1985. It is intended to supplement the formal course notes.

Welcome (J. Wendt)

John Wendt

Good morning, ladies and gentlemen.

My name is John Wendt. I'm the Dean of Faculty at the von Karman Institute, and on behalf of the Director, Professor Ginoux, I would like to welcome you to this AGARD Fluid Dynamics Panel — VKI Special Course on Cryogenic Technology for Wind Tunnel Testing. I think the Director of the Lecture Series, Dr. Kilgore, has, with his Lecturers, assembled a very interesting set of notes. He will say something about those notes in just a few minutes. I think we have a very interesting week ahead of ourselves exploring this very interesting new technology.

Before we get under way, I would like to take just a few minutes of your time to say something about the von Karman Institute for the benefit of those of you who have never been here before.

We were formed as the Training Center for Experimental Aerodynamics in 1956, under the leadership of Professor von Karman, and we were formed, really, as an experiment in international education. The Institute was renamed in Professor von Karman's honor at the time of his death in 1963 and the present name, The Institute for Fluid Dynamics, I think more correctly represents our activities at the present time.

The Institute is affiliated with NATO ... with the North Atlantic Treaty Organization. We currently receive support from 13 of the NATO nations, and we close our budget, if you will, by carrying out contract research for private industries, and government agencies as well, from a number of different countries.

Our faculty, as befits an international institute, is itself international in character. We have six nationalities represented on a faculty of 13 people, at the present time. The total personnel complement of the Institute is about 60 persons.

The students, of course, also are international in character. They come from virtually all of the Western European countries and North America, as well. A typical student year at the VKI will comprise something like 10 different nationalities.

I want to show you a few slides that characterize our activities, and in particular, mention some of our educational programs. When we started the Institute in 1956, we started it with one program that we called our Diploma Course in Theoretical and Experimental Fluid Dynamics. And that course is a 9-month program of research and teaching, in the classical sense, and students who complete that program are typically going off into private industry.

The first slide says something about history, for those of you who enjoy history. You see that this Institute has been active long before 1956 in aeronautical problems. In fact, the site in which we are now holding this meeting was the Belgium Aeronautical Research Establishment. It was founded in the late 1920's and here's a picture of some very interesting helicopter research that was carried out at the VKI back in 1932.

Here's Professor von Karman himself sitting at the controls of that helicopter. They did not allow him to fly it but they did allow him to sit at the controls, at least. So you see that, in fact, research in fluid dynamics has been going on at the VKI, or at least within these buildings, for a long period of time.

Coming back to these educational programs that I mentioned earlier, our Diploma Course is followed by students typically with an engineering degree. It takes about 9 months period of time, and most of our students go on to a professional career at the conclusion of that course. However, some students who are particularly interested in basic research may remain at the Institute and participate in what is really a doctoral program, a program that we carry out in conjunction with national universities, usually universities here in Belgium, but universities in France, Germany, the United States, and the U.K. have participated as well.

On the other hand, there are a certain number of students who are not interested so much in basic research, but more in applied research, and can remain at the VKI for additional periods of time to participate very closely in our contract research program.

In total, we have approximately 50 to 55 students per year who are participating in these three full-time programs.

In addition to those programs, we offer a number of shorter programs. The Lecture Series is one obvious example. We offer 10 of these Lecture Series per year, and the size of this audience is slightly larger than the average, which is about 45 persons from outside of the VKI. But of course, our students are also encouraged to participate in the Short Courses as well, as an excellent way to not only meet the experts in the field who are lecturing, but to meet those of you in the audience who might be future employers of those students and to make some useful contacts.

Other short programs that we organize include, in particular, one which might be of interest to people from universities, and that is our Stagiaire, or short training program. We encourage university students to spend one or two months working integrated, really, into an on going research program at the VKI, and in this way, to learn something about the workings of a fluid dynamics research laboratory and something of the order of 60 or 70 undergraduate students are participating in that program every year.

The international character of the Institute, I think, is shown by this slide which talks about the full-time programs of the Institute since their conception in 1956 and the sizes of the little squares are, of course, meant to be proportional to the number of students that have attended those full-time programs since the beginning of the Institute.

Now, very quickly, I'd like to pass through the activities of our three major Departments. They are Aeronautics, Environmental and Applied Fluid Dynamics, and Turbomachinery. And in each of those Departments, with the aid of a few slides, I will try to show you some of the work that's going on. Now we do have an active computational group, as well, that crosses all of the lines that I've indicated by departmental names; although, in addition, within each Department, there are faculty members who are involved in computation work. In fact, computational work probably now totals something like 40% of our total activity by full-time faculty and students alike, but in slides, one generally is going to be interested in showing facilities or experiments rather than the particular computational results.

I'll pass very quickly through this.

We have a 3 metre low-speed wind tunnel. We're interested in wing-body interactions, swept wings in sideslip, afterbody drag, vortical flows on delta wings including compressibility effects on vortex breakdown, as well as vortical flows on long ogive cylinders at high angles of attack.

Transonic wind tunnel design for reduction of interference effects. The primary interest being the development of techniques to be used in 2-dimensional wind tunnels for corrections on 3-dimensional shapes. The minimizing of interference errors.

Shock-wave/boundary-layer interactions, as shown by this type of laminar 2-dimensional interaction, as well as the swept shock wave interaction studied with laser doppler anemometry and Navier-Stokes codes, as well.

And finally, in the hypersonic regime, we have a Mach 15 to Mach 20 long shot wind tunnel which is capable of very high Reynolds number operation for the study of, again, shock-boundary layer interactions or shock-shock interactions, the types of heat transfer problems, in general, that are faced in re-entry.

In the field of Environmental and Applied Fluid Dynamics, there is quite a wide range of activities that are covered within that Department. Flows around various types of buildings and structures, including cooling towers, as well as the internal aerodynamics, including heat transfer of the flows in those cooling towers. Suspension bridges. The stability of Suspension bridges in cross winds, so dynamic problems, various dynamic structural problems. Also automobile aerodynamics.

This slide reminds me that also there's quite a bit of work done on the dispersal of toxic gases, heavy toxic gases of the type that might be released in an industrial accident. So the dispersion characteristics as well as the way to reduce those concentrations. Heat transfer in gas breeder nuclear reactors and heat exchanger problems in general.

In the field of Turbomachinery, we work in all aspects of turbomachines, compressors, pumps, and turbines, with the exception of those problems involving chemical reactions. Problems involving stall, for example, and prediction of stall and the behavior of a rotary system in stall. The development of instrumentation techniques, such as telemetry to broadcast information out from high speed rotating parts, such as pressure distributions on blade surfaces. The development of high pressure ratio radial compressors. This is an example of a wheel that has been designed and constructed at the Institute. And heat transfer problems, as exemplified by this turbine blade which contains slots and holes for film cooling effects as well as heat transfer gages for measuring heat transfer distributions.

And finally, in the Computational area, again the Navier-Stokes codes developed for examining the techniques themselves and therefore applied to certain classical problems, certain GAMM workshop problems, that are deemed now classical problems for the testing of various Navier-Stokes techniques, in particular, the flow over backward-facing steps.

That summarizes our activities at the Institute and, of course, during the week if any of you have an interest in finding out more about what we are doing, I'll be very happy to arrange for you to see the people directly involved.

I'd like to mention a few logistic considerations now.

First of all, we will take lunch each day in the restaurant of the Ministry of Communications and Transport, which is about 150 metres in that direction, further on through the Institute. You just follow someone else who seems to know where he is going and you will probably end up at the right place because there are a number of familiar faces in the crowd here, people

who know how we're organized. The lunch breaks are meant to be relatively long, an hour and a half or so typically, in order to give you good time to meet with one another and to exchange some information privately. That also occurs very often at coffee breaks, and their will be a break each morning and afternoon.

As far as the other arrangements are concerned, we do invite you to a cocktail in the canteen ... which is the place in which you registered this morning ... at 5 o'clock this afternoon.

That means that today the bus will leave at 6 o'clock. On other days it will leave at 5 o'clock, however with two exceptions. As you will notice from the schedule, we are giving you Wednesday afternoon free to do some shopping or some tourism, and we will also close the meeting at noon on Friday. That means that on Wednesday and Friday the buses will leave at 1:30.

If you have any questions concerning arrangements, I've written the name of our Secretary, Madame Rigaux. Her office is located on the first floor ... not the ground floor, but the first floor ... in the next building, ... which you must enter from the front door where the sign says "Reception" ... our Administration building.

Also, within that building, you will find a Telephonist in case any of you wish to make telephone calls, you just place your calls with her and she will connect you and charge you for those calls afterwards, unless they are local calls, of course.

We will organize two tours, and they will take place tomorrow at 1:30 and Thursday at 1:30, with the people participating in those tours meeting here in this room at 1:30. And what I suggest is that ... first of all, the tours are entirely optional, some of you have seen the Institute on a number of occasions ... what I suggest is that those of you sitting in the first 4 rows who wish to make the tour please do so on Tuesday at 1:30, and that those of you sitting in the remaining rows, please make the tour on Thursday at 1:30. That will keep the numbers approximately equal, and we will divide each group into two parts so as to give you some more individual attention.

Finally, for reasons that I need not go into, I would like to call your attention to the last note on the board. It's perfectly all right if some of you wish to leave your automobiles at the Institute during the week and simply go back and forth with the bus. I know that a certain number of participants prefer to do this. That's perfectly all right. But, if you do this, you must give to me the number of your license plate and your name so that we have that information on file. Otherwise, you may come here the next day and find that your car has disappeared. It's simply no longer a good idea to leave unidentified cars next to buildings which are associated with NATO. That summarizes that matter, I think, clearly enough, if you've been reading the newspapers over the weekend.

Now I'd like to turn the meeting over to our Lecture Series Director. But, first of all, I would like to call your attention to the fact, again, that this Lecture Series is co-sponsored by AGARD, and Mr. Bob Rollins from AGARD is here, ... he's raising his hand over in the corner ... so if any of you need to see Mr. Rollins, who is the Executive for the Fluid Dynamics Panel of AGARD, you know where to find him.

Now it's with great pleasure that I turn the meeting over to Dr. Robert Kilgore, who is the Lecture Series Director, and has done really a magnificent job, I think, in putting together a very interesting program.

Dr. Kilgore is Head of the Experimental Techniques Branch at NASA Langley and will be in charge of the rest of this meeting. I will act as the Local Coordinator and, therefore, will be the target of all problems that you have during the week and will do my best to solve them.

So, Bob.

Introduction to Special Course (R.A. Kilgore)

Robert Kilgore

Yes, all problems should be addressed to John.

I'm going to make this very brief so that we can get on with the Special Course.

Doing this reminds me ... although I have no personal experience ... of being pregnant. Whether you are ready or not, after about 9 months it's going to happen. And it's about the same period of time that we've had to organize and get this particular Lecture Series together. Most everything has fallen into place very nicely. At the end of the week we'll make an assessment of how well things actually have gone.

The bound volume contains all but one of the papers. At the end of the coffee break, which we will take after Mike [Goodyer] finishes, in roughly an hour, we will have these packages open (pointing to several packages at the front of the room), the papers that are in here in French will have English translations which will be available. There will be other material ... assuming the mails have gotten through ... that we will hand out at that time.

I mentioned to one person this morning ... I think it was Dick Cole, coming from the west coast of the United States. Those of you from North America get to nod off this morning but not snore. It certainly is a tremendous jet lag for those of you who arrived yesterday.

With that, and perhaps leaving out a few things that could be said, let me introduce our first speaker, Mike Goodyer. One of the bits of material that will be handed out will be a package containing biographical sketches of all the lecturers. And the purpose of the biographical sketch is to keep me from standing up here and forgetting the important things and saying the trivial things. The important things, in fact, are printed.

Most of you ... since we don't have the material ... most of you do know Mike and his very long association with cryogenic tunnels. He hosted, in April of 1979, the First International Symposium on Cryogenic Wind Tunnels. He was involved, more than intimately ... it was his idea in 1971, I think it was ... Mike, it's getting so far back it's hard to remember ... it was Mike's idea that we, in fact, cool the test gas in order to increase the Reynolds number, which is, of course, the basis of the Cryogenic Tunnel Concept. In addition to the International Symposium in April of '79, Mike was the Director of a Special ... rather, a Lecture Series held at VKI in May of 1980 and in the United States, at Langley, I guess in the same month, May of '80. This Special Course is a follow on to that Lecture Series, and I felt it very appropriate that Mike Goodyer tie the two together with the opening presentation at this Special Course. So, the extra details you want to read on Mike will be in the hand out. And with that, let me let Mike take over.

Lecture No. 1

Introduction to Cryogenic Wind Tunnels (M.J. Goodyer)

Mike Goodyer

Can you hear me? Is it transmitting? O.K.

Well, good morning, ladies and gentlemen.

I interpreted my task, this morning, to deliver to you a relatively basic introduction to cryogenic wind tunnels, which will include some historical details of the era running up to the beginnings of the development of the [cryogenic] wind tunnel, so it is slightly historical as well as rather basic from the fluid mechanic point of view.

Now let me just get the slides organized. That looks like the advance button. We've moved on 2 then, so let's go back.

Now we have 1.5 slides.

(Laughter)

Bad dreams are made up of moments like this.

(Then follows the first lecture)

(There was no discussion following either Lecture 1 or Lecture 2)

Discussion following Lecture No. 3 (D.A. Wigley)

Stan Griffin

Most materials have better properties at cryogenic temperatures. We expect to run the NTF models at both ambient and cryogenic temperatures or in an ambient tunnel prior to testing in the NTF. Is it true that the strength of the model would be reduced at the ambient temperatures?

Wigley

Very much reduced, in that case.

Griffin

And in the case of Nitronic 40, from what I remember, the Nitronic 40 model would not be strong enough to go into a conventional tunnel. Is that correct?

Wigley

Probably not a conventional fully pressurized tunnel. No.

Griffin

As I remember, Nitronic 40 has very good cryogenic properties but not very good room temperature properties.

Wigley

Well, if you turn to the appendix of my personal albatross, we ought to be able to pull the figures straight out of that, because that's one of the materials ... yes, Nitronic 40, ... it's 400 MPa at room temperature, which is, in fact, quite low, and 1034 at 77 K. So ...

Griffin

It's degraded more than, say, maraging 200.

Wigley

That's right. Essentially, a ferritic steel has a relatively high ratio of yield stress to ultimate stress. Whereas, an austenitic steel has a relatively low yield stress and a long degree of work hardening before it gets up to the ultimate. And, of course, it depends on ... I mean, you're not really designing to any code ... if you're designing to ASME VIII, where it would be a quarter of ultimate stress, you'd get a different result than if you're designing to one of the BS codes which allows you to design on two thirds of the proof stress, where you get a better design point for the maraging or ferritic steels than you would get for the austenitic steels.

I think, again, it's the problem that any multi-roll aircraft or multi-roll component ... you lose something. So if you're asking that a model will work at room temperature and cryogenic temperature, you're making life even more difficult than it is already, just going cryogenic.

Griffin

And yet, in a practical sense, I think the model manufacturer, or the model designer, will want to use his model in both cases. He can't do all of his testing at cryogenic temperature. So he has to have both capabilities.

Wigley

That's right. So ... I mean, something's got to give. You can't have everything.

Kilgore

Dave, I saw some other motion. If you want to direct traffic with the questions ...

Unidentified speaker

You told us that welding for maraging steel was possible. Do you have any experience in the behavior of this material in respect to fatigue life?

Wigley

I personally don't. I said that ... I think you can electron beam weld maraging steel. I don't know about ordinary standard fusion ... you know ... metal arc welding ... to the extent as to how much it degrades the properties. But undoubtedly, in order to get maraging steel into the toughness condition to allow it to be used at low temperature, the parent metal is already only just good enough.

Now virtually any welds, where you have got the columnar grains and the recrystalization, you've got a lower toughness in the weld zone than you have in the parent metal. So I very much suspect that you could not do an ordinary bulk welding process on a maraging steel and still pick up the minimum toughness required for a tunnel application.

Now, the electron beam weld with a laser, where you've got a very much better control ... O.K., that's something different. But, actually physically joining large sections together using conventional fusion welding, I don't think would be a sensible fabrication route.

Unidentified speaker

(Unintelligible question)

Wigley

Well, again, I think that there is experience building up that it is possible and Stan [Griffin] knows more about it than anybody else in the room.

Griffin

We did some samples of maraging 200, and we did laser weld joints, and we did structurally test before and after, and we didn't see any degradation.

Wigley

But you would agree that ordinary fusion welding ...

Griffin

As for fusion welding, and its use in a cryogenic environment, ... well, I don't have any experience. We didn't try it.

Wigley

But your gut feeling is ...

Griffin

I would tend to feel that it would not work.

Wigley

Yes. That's what I thought.

C.P."Buddy" Young

Dave, the EB welds on the X-29A model ... the properties were unchanged.

Wigley

They were? O.K., so there is, you know, there is experience building up now. And again, all that second batch of slides that I've showed you on the dimensional stability ... the larger specimen ... that was on the new titanium, cobalt-free maraging steel. And the experience building up there, so far, looks good. It looks as if it's got a better toughness, but that all the other advantageous properties of maraging steel are maintained.

Yes?

Unidentified speaker

It's a question again about maraging steel. You said that the 250 grade maraging steel is used for stings and for model support, and that the 200 grade maraging steel is used for model parts, because the low-temperature toughness is, of course, too low, for the 250 to use it for model parts. So, in fact, that is a question of design philosophy. You are taking larger risk for the model support and for the stings.

Wigley

I think ...

Unidentified speaker

Of course, if the sting breaks, the model goes.

Wigley

That's not my expertise. I bow to a lot of others in this room.

Young

Dave ...

Wigley

I would rationalize it, basically, that the sting is a very much simple solid of revolution, you can get a nice surface finish on it, you get the stress concentrations out of it. Whereas a typical model, you are going to have holes cut in it, you're going to have changes of section, you're asking more of the model for safety ...

Young

Dave, we do not use 250.

Wigley

You don't use ...? I thought somebody was using 250.

Young

It was used before. For balances. But not for NTF.

Wigley

O.K.

Kilgore

You still gave a good reason. I think the sting is much easier to analyze as well as to finish.

Wigley

Yes. It was considered for the sting.

Kilgore

I'm not sure.

Young

Not very long.

(Laughter)

Wigley

Well, see, there again it's a question ... you know, a question of evaluating the risks, and looking sensibly at where this trade off between strength and toughness is.

Unidentified speaker

I want to know which is the concept we look for higher stress and does it affect us comparing with real life model we are using today.

Wendt

Can you repeat the question, Dave?

Wigley

It's to do with how you chose the sort of stress intensity factors at the design stage of the model and what experience that has had in actual use of the model in the tunnel. Is that correct?

Well, as far as I understand it, that information is sort of only just coming out inasmuch as if we're talking about the National Transonic Facility, it's only flown one or two models.

I think in terms of the 0.3 meter tunnel, you have a less demanding environment. Many of them [models] are 2-dimensional structures. And that the experience has been, for example, with the beryllium copper model, which did not have the intrinsic toughness, that nevertheless, it performed satisfactorily in service.

But, you know, where do you ... it's like anything else, where do you balance off the risk against the advantages? I mean if I had a pressure vessel sitting underneath my chair, I'd want a damn sight higher safety factor on it than if it was at the bottom of somebody else's garden. Perhaps that's a rather personal way of looking at it, but, you know, safety factors are there to guard against some form of potential failure.

Now, you take the case of a space rocket. You couldn't design a space rocket to ASME VIII. It would be so damn heavy and thick you couldn't get it off the ground. So, in order to make a viable space rocket, you have to have a smaller safety margin. You have to have the fracture toughness type analysis to decide what are the risks. Now, perhaps I'm still too much of an academic to really be involved in risk taking.

Unidentified speaker

Because some metals have higher life ... stress life, and lower stress intensity factors also, but which is important? Higher stress intensity factor or ...

Wigley

I think perhaps you'd better direct that question to Buddy Young. Buddy is at the sharp end of the business. I'm the academic ...

Kilgore

This is the perfect place to take the coffee break, because Dr. Young is going to get into the details of model design and fabrication for the NTF. ...

Wigley

And address that question.

Kilgore

... where things like this are specifically addressed. So now's the time to enjoy the coffee and then we come back and learn all these details.

Be back in 30 minutes.

(Pointing to the clock on the wall) This is a trick clock on the wall. It's 4 minutes fast.

Discussion following Lecture No. 4 (C.P. Young)

Kilgore

Dr. Young has left sufficient time for almost any number of short questions, and perhaps several detailed questions. Buddy, let me let you field them from there. You can see better than I who is anxious to ask a question.

Young

O.K.

Goodyer

Did the specimen that found its way around ... filler material, was that ... I suppose it's basically a bonding test ... was that carried out in a wind tunnel environment? By that I mean, with rates of changes of temperature fairly typical of those to be expected ...

Kilgore

Could everyone hear the question? O.K. If the question comes through soft, be sure and repeat it, Buddy. Apparently they heard that one.

Young

Maybe. The question had to do with whether the fillers were applied in a wind tunnel ... representative of a wind tunnel environment.

Goodyer

Yes.

Young

Actually, what was done there, and what we typically do, is not ... after we take the specimen and put the filler materials on it, it's subjected to a very rapid temperature drop. We have a cryo tank at Langley, which allows us to go down in temperature very rapidly, so it's a more severe test, if you will, than it would be in a wind tunnel. Now those same materials, there, that you see ... at least some of them, I know ... have been put on actual models as well as calibration rakes in the NTF. So it sees ... those materials see the actual temperature transient of the model. But, basically, it's a more severe test than what the model would see.

Goodyer

Is it a bit of a dunk?

Young

We have a tank and a tray. We don't actually immerse it but we can bring it down in temperature very rapidly. We put it right over the liquid nitrogen at the bottom of the tank.

Goodyer

Thank you.

Griffin

Was that specimen aluminum, there, Buddy?

Young

Yes.

Griffin

But that's not the material that the model is going to be made of so if you run that at cryogenic temperature that isn't realistic.

Young

No.

Griffin

Then, what we were doing for you, we had maraging 200. I think that answered, really, what Mike was talking about.

Young

Yes, but the spar specimens that I showed you, were steel.

Griffin

They were steel.

Yes, it's really kind of surprising on some of this stuff that has a real thermal mismatch, we don't see much happening under load and under cryo cycling.

Griffin

I have one little question.

Kilgore

Ask it very loud and we'll not have to repeat it.

Griffin

With respect to the lower safety factors on the model, obviously, in real life, when you come to test, you're working with predicted loads, and if those predicted loads aren't correct, then you are ... you could be in trouble. Are you going to monitor the loads that you see in the tunnel with either the balance or with separate strain gages?

Young

The answer is yes and no.

Right now, these initial models ... the only data we're getting off the Pathfinder is the balance data. So we monitor the model from that point of view. On some of these models, which I have not talked about, which are going to go to very high q's, ... upper end of the test envelope ... we are going to go to put strain gages on those models. We sure are. We've already identified those that we are a little bit uncomfortable about in terms of knowing what the loads are. In particular, the dynamic loads.

As a matter of fact, we want to put in a system, Stan, that's going to be permanently in the wind tunnel facility which will ... we can acquire the data, process it, and do a spectral analysis on it and that sort of thing, for selected models.

Yes?

Luck

Do you see any limiting pressure in the NTF as to models using materials you've got at the moment? And to avoid high loads, do you see yourself putting a ceiling on pressure?

Young

Well, for those airplane models that we've designed so far, we don't have a problem in terms of meeting the desired test envelope. Now, we've got some body of revolution models that the researcher wants to go up to something like 7000 psi in q. From a strength point of view, we've been able to design those models to do that. And also from a stability point of view. The problem is going to be more that of holding ... making sure you're stable under those conditions, and in those situations, we're going to have to be instrumented so that we can see what the dynamic load components are. But, we're going to run into some that we're going to have to give a lot of attention to. But, so far, we're doing that.

Kilgore

That's a long enough pause without a question to stop.

Discussion following Lecture No. 5 (C.P. Young)

Kilgore

Buddy, plenty of time for questions if you want to field them.

Young

Questions? Yes.

Jean Christophe

In your Table 7, you have a large difference for total cost factor for maraging with grain refined or not. What is the reason for this large difference with grain refined or not?

Young

Which ...

Christophe

On your Table 7.

Young

Table 7. O.K. The question has to do with Table number 7.

Christophe

It's about the total cost factor for maraging steel.

Young

O.K. I'm on Table 7. Now would you repeat the question, please?

Christophe

The question is, I notice there for maraging steel 200, you have two cases ... with grain refined and not refined. There is a lot of difference in the total cost factor. How do you explain this large difference? 1.10 and ...

Young

The first is 0.85?

Christophe
Yes.

Young

O.K. As I said yesterday, when we went through the grain refinement process, we were being told that the material machines much better in the "grain refined" condition than in the "as received" condition.

Christophe

Because during machining there is not deformation?

Young

The material is very stable. Either way. Very stable, as Dave Wigley said yesterday. Very stable both ways. The difference there is based on our experience with machining the Shuttle model component out of a 450 pound plate, compared to experience in machining other model components out of the non-grain refined material. What it says is, based on this cost factor ... and it's not ... nothing magic about it ... purely an estimate ... that the machining time should be about 75 percent for the grain refined as opposed to the un-grain refined material.

Unidentified speaker

You showed us an epoxy airfoil. What would you use that for? Because surely you can't get a surface finish on an epoxy airfoil that is smooth enough to serve as a model.

Young

Well, we really don't know what we can get yet. That's part of the process that were looking at. When we started looking at composites, we were told that you can never get the kind of surface finish that you can get out of metal. But ...

Unidentified speaker

Do you think you can?

Young

Pardon?

Unidentified speaker

Do you think you can?

Young

Well, I'm going to ... I think we can come close. What I'm doing right now ... I think I mentioned it yesterday ... is building some instrumented composite horizontal and vertical tails. Now, the surface finish requirement for those components are not as stringent as for the wing. But, I don't think we can get to 8 to 10 rms, but I think we can maybe get around 30. But, I was surprised that we could get something that smooth. The 2-D that was tested is much smoother than that. The problem is measuring it. We're not sure ... we say 8 to 10 ... we're not sure we can even measure that with some of the equipment that we've got.

Unidentified speaker

This implies that if you can get a good surface finish you can also get a good ...

Young

Tolerance?

Unidentified speaker

... geometrical form.

Young

Yes. Yes. You see ... what you do, after you lay that up, you can machine that down to pretty close tolerance. I don't know that we can get plus or minus a thousandth. It's tough to do that on them now. But, anyway, we're trying to find out how good can you do.

Yes?

Another unidentified speaker

You have compared pressure results with such a pressure wing with a metal wing?

Young

The ... Maybe Bob can help me out here, but, as I understood it, the raw data from the composite 2-D versus the metal 2-D looked good ... the correlation.

Christophe

Do you know the overall cost of a model like Pathfinder I? The cost of this model?

Young

No I don't.

Christophe

You don't know?

Young

The reason ... The answer is "a lot."

(Laughter)

Well, the reason that I can't give you a cost figure is that's our developmental model. O.K. We had to do an awful lot of developmental work ... proof of concept. Everything that went into that design had to be proven some way or other. So we just gave up trying to even track the cost of that. The Boeing model, you can't draw a fair comparison from that, because it doesn't have as much instrumentation. It's nothing like it.

But, what we're going to try to do ... we've got a number of models in the system, so that once we get these models in, we're going ... and we are breaking out design versus fabrication costs ... so, for the different types of model, my plan is to assimilate that data so that we can get a feel for what is it really costing us. I've been asked that question many times.

Kilgore

He only has eight digits on his calculator.

Young

Any other questions?

John Tizard

Do you completely warm the model up for model maintenance?

Young

The conditions that we've been working toward ... and maybe Ed [Bruce] can help me out here ... is that the model will be heated and we are expecting to work on the model which will have surface temperatures around 40 degrees F. This is for quick access model change type of thing. Is that around ...

Bruce

You've got to get it above the dew point of atmospheric air or you'll have water going down the [pressure] tubes.

Young

We don't have that experience yet, John, in terms of finding out how well we can warm it up. You know, when that thing is ... you're working on something that's on a sting and on the other side of that housing wall there, the gas is very, very cold. So, you've got a lot of heat loss there. And I imagine what we'll see is that we're going to see a temperature gradient along the length of the model, certainly. This is one of the problems that we've had to address in determining if we can put fillers on and how we're going to cure it, and that sort of thing. And we're also worried about frost formation when we back out of there. On the model.

Kilgore

Well, thank you again for a very nteresting and stimulating presentation.

It's a pleasure to see how things go.

Five years ago, the major concern was "can you build the wind tunnels and make them operate at cryogenic temperatures." Now, the concern ... major concern is "can you build models and make them work," and were hearing that we can. We even heard a prediction that five years from now, when we have the next one of these, no one will make a presentation on model construction. Which I think is great.

After the coffee break ... which will last thirty minutes, by your watch, not by that one, be back by 15 till 11 ... After the coffee break we'll go into another mode ... the concern over instrumentation in cryogenic tunnels.

So, enjoy your coffee break.

Discussion following Lecture No. 6 (M. Bazin)

Kilgore

Thank you Maurice.

Let's have one or two questions, and then, there are items on display. And, as Maurice said, they're still in use so they shouldn't be dropped too far, at least.

Wigley (in a whisper to Kilgore)

He said they shouldn't be touched.

Kilgore

Oh! Touched! They shouldn't be touched! Yes. Dave was listening closer than I. Don't touch but do look, either before we go to lunch or afterwards.

So, Maurice, if you want to direct traffic on any questions here ... perhaps 5 minutes worth. We're not late at all.

Ron Law

On the design of the cryogenic balance, has the balance been designed to optimize the x measurement by finite element analysis, and was a three-dimensional program used? And if it was, what type of mesh was used?

Bazin

It was a finite element program. And we used a program which is coming from the Lockheed Company and which is called REXBAT. And this program works for strain and for temperature.

Does that give you a response?

Griffin

The deformation measuring system, how accurate is it?

Bazin

Ah. That's a difficult question. We hope that we will obtain, in a large model, 0.05 degree on rotation and 0.1 millimeter. I am speaking of a large model and that means that we observe the large model, up to 4 metres, from about 4 metres. The results which were obtained in the laboratory ... I think we ... this was the first attempt, a very simple prototype ... we think that we obtained 0.2 mm on the circle at near 3 metres.

Griffin

And this information, is it on line? Do you get it immediately?

Bazin

You mean this information is available or ...?

Griffin

No. Is it available immediately, in real time?

Bazin

Oh, yes. Yes. This was not a very strong request. But we consider that if we have the results in, say, one hour it would be a good result. But, in fact, the system, which is developed by DERO, is supposed to give the results in a few minutes. Or in a part of minute. We don't know exactly because the full thing is not made, it's only a prototype.

Law

On the optical position measurement on the trailing edge, there is no mention, that I noticed, of a test target. How is the correction made for the changes in the refractive index of the gas?

Bazin

I'm sorry, I m not sure I understand the question.

Law

As the gas density changes, the refractive index will change.

Bazin

It does not change anything. You are speaking of the "torsiometre" or the "recepteurs?"

Law

Les recepteurs.

Bazin

Above the trailing edge? Yes. And your question is relative to a change of density?

Law

Yes. Changes in the refractive index of the gas.

Bazin

You might have small changes in light transmission due to refractive effects in the flow. They are reported to be small behind the trailing edge and ignored. The calculations can easily be made from a typical flow distribution. You will find the full response to your question in the paper which is given as a reference and which was given in Amsterdam by Mr. Surget.

Kilgore

Well, thank you again, Maurice.

Discussion following Lecture No. 7 (A. Mignosi)

Kilgore

Thank you Andre for a very interesting paper.

It's coming through again and again that having high Reynolds numbers is not ... it's necessary but not sufficient to ensure proper aerodynamic data out of wind tunnels.

We have time for a couple of questions before those of you who need a quick coffee fix start wandering out. So, Andre, if you will direct, again, the traffic from the questions. If it's not loud enough for those in the back to hear, if you will repeat the question as well as the answer.

Goodyer

I have a question ... I think a statement, first of all. On the subject of surface flow ... surface streamline visualization.

A technique was developed at Southampton University using propane as the marker. The objection to that was the fact that we needed to use a pigment to show the flow pattern, and the pigment, having finite particle size, could itself affect the flow. That was the objection. I believe that Douglas Aircraft Company, following that work, and again using propane, found some kind of dye that could be added to the propane that would leave a mark on the surface, but, I believe, not materially effect the surface condition.

Mignosi

Yes. We ... I think that surface visualization will be a large help for the experimenter. And probably we will test also this technique. But with oil, for instance, you have also the possibility to fix the transition with the particles.

Goodyer

Yes.

Mignosi

If you want, I have a picture on it. And we take some precaution for that. For instance, in this case we have observed the transition with oil. And for that, we put the oil very near the point where transition occurs. Because, if you put, for instance, the oil too near the leading edge, the displacement thickness is little and all the particles can fix the transition. For instance, here, you see that there is one particle, at least, that has fixed the transition. And we have made this type of picture. But if we can do that in cryogenic (unintelligible) it will be very (unintelligible). We think that possible with a pigment in ...

Goodyer

Well, I think not with a pigment. I think the technique that Douglas developed was specifically for application to high Reynolds number cryogenic wind tunnels, and used not a pigment but something else. I can't remember what that something else is, but I think they have done enough of the ground work to make it possible.

That was a statement. I have a question as well.

A brief question then. On your figure 28 in the text ... in the upper half of that diagram, which is applicable to a laminar shock boundary layer interaction, there seems to be a dip in the Mach number distribution which I thought you ... maybe I misunderstood something ... I thought you were associating that dip with transition.

Mignosi

There is first separation of the laminar boundary layer. And after that, the transition in the shock wave interaction. But when we (unintelligible) we see a (unintelligible) laminar part there is that sort of separation (unintelligible) is that the turbulent. (unintelligible) It is the case of a very complicated interference in the separation.

Goodyer

O.K.

Kilgore

A long enough pause to call a halt and have coffee.

Thank you very much, Andre.

Discussion following Lecture No. 8 (J. Christophe)

Kilgore

Thank you, Mr. Christophe, for a very interesting paper.

Quite often projects are killed off early when you don't do your homework and show that you can afford to actually operate a tunnel like this. This study, certainly, is an ongoing thing, and I think you've done an excellent job of pulling it together and considering all of the elements.

We have time for a couple of questions. John is nodding his head in agreement. We're spot on 5 o'clock by my watch, as opposed to the clock on the wall. So, if you will accept questions from the audience.

No questions?

O.K., Stan.

Griffin

Obviously, the cost of running the tunnel is very high, perhaps in relation to the model cost. We talked a lot about model costs and saving money on the model. But now, obviously, productivity perhaps is even more important. When you talked about the model injection system, are you suggesting two models, two similar models, one replacing the other one? Or two different configurations?

Christophe

You speak about the model cost ...

Griffin

Yes.

Christophe

... and if it's necessary ... if the injection method ...

Griffin

Yes.

Christophe

... has some connection with the model cost ... with the model ... with the construction of the model? This is your question?

Griffin

Yes.

Christophe

At this time, I don't consider this. It's a very important point that the model ... for example, on classical model in wind tunnel we have some part we modify some time. It's not so clear it's possible for a fighter, for example, to modify. Perhaps it's better to have a wing per configuration. But, I don't know. That is the reason for my insistence to say it's necessary to look very carefully at a realistic program. For example, it's clear, it's in my paper, ETW people, has two programs by German people. One for fighter and another for civil aircraft. And it is very clear that for the fighter it is necessary to modify the configuration very, very, very frequently. We have some connection with a facility and production of the model and the modification of the model, it's clear. But we have not considered this in detail.

Kilgore

Thank you, again.

Discussion following Lecture No. 9 (J-B. Dor)

Kilgore

Thank you, Mr. Dor.

It must please many of you to see good aerodynamic data coming out of cryogenic wind tunnels.

If we're ... of course, well ahead of schedule. If you would entertain questions from the audience, if there are any. If there're none, we'll act accordingly.

Unidentified speaker

Why is the head of the pitot probe made of wood?

Dor

Because wood has a relatively low thermal conductivity. We tried to do a probe with metal ... with steel ... but there was always an influence of the support on the model. And wood has a relatively low thermal conductivity and as we tested wood probe, it was good.

For a good analysis by this is to make an estimate of the gradient in one direction and then to come back. If you find the same thing, it is good proof that the probe is good.

Pat Clark

Is the fact that the composition of your gas changes during the run cause you any problems? Like, you start with almost all air. As you put in more and more nitrogen to cool it, you're changing the composition.

Dor

Yes. But the composition, I said, .. there is a driving air flow rate and a [liquid] nitrogen flow rate. And the final composition is made by these two flow rates. The initial air is of no importance. And what I said about the composition was ... I don't think it was written ... it is made of these two flow rates, a long time after the starting of the tunnel.

Clark

Does the tunnel run long enough, though, to get to that state? Because, the one curve you showed, your nitrogen flow, at least, was still varying. In your figure 4, your nitrogen flow rate never actually comes to equilibrium.

Dor

What figure, please?

Clark

Figure 4. The top one on the right-hand side. The liquid nitrogen flow rate is never actually constant. It isn't varying very much.

Dor

Ah. Yes. I can explain what it is.

To cool down the low velocity flow we inject an important quantity of liquid nitrogen. When the flow temperature is near the final temperature, the flow rate is reduced, and begins the closed loop regulation with the model flow temperature. This is during the first phase.

Then, the profile is introduced. During the second phase, when the Mach number and the pressure are raising, the liquid nitrogen flow rate is independently calculated. Only calculated. There is no regulation. It is calculated to compensate roughly the driving air flow rate and the compression effect. And when the second phase is finished, the temperature is not too bad. If you want. And the closed loop regulation is started new. And now then it is the third phase.

Clark

I understand that. The point you were making about composition was that if you come to a point where your ejector air flow is constant, and your cooling liquid nitrogen flow is constant, then you have effectively wiped out all of the air you started with in the tunnel, and the composition is constant.

Dor

Yes.

Clark

I'm saying, from this figure, you never come to that point where the liquid nitrogen flow is constant, so your composition could be varying a little bit with time during the whole of your run. And I'm just asking, does that cause you any problem?

Dor

I don't know. We have no problems. Perhaps if there are problems, we haven't seen them.

(Laughter)

Kilgore

May I add a little bit to that. I guess, since air is roughly 80 percent nitrogen, there certainly is not much change in the total composition, even though there is this slight variation in the level of injected liquid.

(Speaking to Mr. Mignosi) Would you care to address that in more detail?

Mignosi

We can tell from the composition of the air, which is 20 percent oxygen, to 10 percent when we mix about the same quantity of air with liquid nitrogen. But for all the Mach numbers in the domain, for instance, we always take a ratio of the specific heats of the gas, gamma, of 1.4. It seems that this value is a good value for the gas.

Clark

It doesn't appear to be a problem.

Mignosi

It doesn't appear to be a problem.

Clark

One other question. In your figure 1, on the air supply system for the injector where you show both air or gaseous nitrogen. Can you actually run it with all nitrogen or has that not been implemented? Right at the top on figure 1 you show the compressor, then the drying plant and then you have a box there that says air or gaseous nitrogen.

Dor

Yes. Because we are equipped to load the high pressure air receiver with high pressure gaseous nitrogen obtained from our storage. But we never use it. All the tests we have done till now have been done with air as driving gas and nitrogen as cooling liquid, because we are afraid of the safety problems, essentially.

Ralph Scurlock

I want to ask a small question and make a point. On page 12 of your English notes, you mention the size of the adaptive wall sections, and you say that it's 0.39 millimetres wide and 1.32 metres long. Is that first figure correct?

About two thirds down the page. The walls are 1.3 millimetres thick. And then you say the size is 0.39 millimetres wide.

Dor

Yes. And 1.32 metres long.

Scurlock

But is that width correct?

Dor

Yes. I believe ...

Wigley, and others.

Metres, not millimetres!

Dor

Oh, yes! Metres!

Scurlock

O.K. Thank you. O.K. Now I'd like to make a point about the particles.

Dor

Yes. That is very important.

Scurlock

Referring to your figure 27, when you talk about particles, and (unintelligible), I'd also like to just query the fact that the pressure drop across the filter rises during the second half of the cycle.

The point I would like to make is that in some of the work we are doing at Southampton, we've discovered that water dissolves in liquid nitrogen and liquid oxygen to a very surprising extent. It will dissolve at one atmosphere pressure to about 10 parts per million under saturation conditions. And at pressures up to about 20 bars, which I notice is the pressure in your intermediate storage, the solubility could rise another factor of 10 ... up to about 100 parts per million, under equilibrium conditions. Now if that water is there and then you inject it through your sprays, you're going to have a particle problem.

Now that water can be absorbed during exposure of the nitrogen to the atmosphere or to ice during the manufacturing process. And I would just like to bring this to your attention because I think one has to watch your housekeeping, as far as

liquid nitrogen is concerned, to ensure that the actual water up take in your nitrogen tanks is kept at a sufficiently low level that your not going to be plagued by this problem.

The other thing I ought to mention, that is that, generally, if you've got a liquid nitrogen storage tank, and you happen to look inside, you'll see that the bottom is full of frost anyway. That's deposited ice. And any stirring is going to cause that ice to dissolve back into the nitrogen at your ambient conditions. So, I think if you are going to find that particles in the flow are going to be a problem, then you've got to do something about keeping water out of the nitrogen in the first place. Like the CO_2 as well.

Dor

Yes. But for us, we knew that when we heat this gas, our drying system was not very performing. So we were not astounded to find ice, also. Now the drying system is better, but we have not done again such tests.

Scurlock

Certainly, in the future, I think this is a problem you have to face.

Dor

That is correct. Thank you.

Unidentified speaker

What type of transition fixing did you use and how did you check whether it was working or not?

Dor

We used carborundum grains bonded to stick in a line. And, I did not understand the rest of ...

Unidentified speaker

How did you check whether it is working or not?

Dor

(Nods to M. Mignosi)

(Laughter)

Mignosi

Yesterday, I presented some (unintelligible) to fix the transition. We pick the height depending on the thickness of the boundary layer at the location where we want to fix transition. We calculate. We can also change its height and see if it's fixed the transition or not. We can finally measure the drag coefficient. If it's right, we are in the turbulent state and have changed the (unintelligible) transition.

Kilgore

This may be a good time to do a few bits of business.

Ralph [Scurlock] has raised a point by catching an error. If anyone else sees something that they think is an error, circle it, call it to the attention of the authors, because the notes will be reprinted and we might as well purge them of as many typographical errors, or otherwise, as we can.

That brings me to the point that you will be mailed the reprinted set of notes. Make sure your name and address is as you would like to have it on the list of attendees. Otherwise, you won't get anything, perhaps.

What else do we need to do, John?

John Wendt

There was one more question, I think, over there somewhere.

Kilgore

O.K. I'm sorry. I didn't mean to interrupt the flow of questions. But while I was on a roll there, I thought I'd get up and say that we, as authors, do appreciate having called to our attention any errors that have crept in.

So we'll continue with the questions.

Unidentified speaker

Do you make for each Reynolds number separate wall adaptation?

Dor

I don't understand.

Unidentified speaker

For each Reynolds number, a wall adaptation? For each Reynolds number you have compared the positions?

Dor

Yes. We have compared the solution.

Unidentified speaker

I mean the wall shape. Between the three Reynolds numbers.

Dor

Yes. The same.

Unidentified speaker

The same?

Dor

Yes. We compared them for that.

Unidentified speaker

Are you sure?

Dor

(Looking to M. Mignosi) Help!

(Laughter)

Mignosi

You have a slight change. The first one is that you change the equation. And the second one is that you change the boundary layer to turbulent (unintelligible) and we take into account this parameter by having the free streamline we want the computation to compute the boundary layer. We add this to the displacement thickness to adapt the wall. It is a slight change and we observe this change for tests at different Reynolds numbers.

Unidentified speaker

Coming back to the figure 28.

Dor

Twenty eight.

Unidentified speaker

(Unintelligible question)

Dor

We are running with the driving gas, air, and liquid nitrogen, cooling gas.

Unidentified speaker

(Unintelligible question)

Kilgore

Could you repeat the question? I didn't catch it.

Dor

If we would have only nitrogen ...

(Some discussion in French)

It is the same.

(More discussion in French)

Unidentified speaker

It would change by 3 or 4 or 5 degrees [kelvin], I think. That order of magnitude.

Dor

Yes?

Scurlock

Can I ask another question?

What is your policy about the safety of personnel in the vicinity of the tunnel when it is operating?

Dor

We think that the best thing is that everything operates well.

When you follow the normal test process, everything is good. But if we have a lot of problems, for example, if the pre-cooling device doesn't operate well, for example, if we have problems on measurements on scanning valves, and so on, too much such problems stop the run. And it is always very difficult to start again the run. And in this condition, I think safety is not so good as when everything is well tested before operating on the tunnel. So we try to well test all the equipment of the tunnel. Because when we made the first profile test we had certain difficulty with the pre-cooling device and fog (unintelligible). All material problems, mechanical problems and so on. And for safety it was not good, I think. We had planned these problems were solved before that.

(Some discussion in French)

There is nobody in the room.

Scurlock

Nobody in the room?

Kilgore

I think that was the point that Ralph was making. Not to be around the tunnel when it was operating.

Thank you, Mr. Dor, for a very interesting lecture and discussion.

Discussion following Lecture No. 10 (G. Hefer)

Kilgore

Thank you.

Even though you expressed some concern as to whether it would work or not, I have no doubt that it will. Those of you who are familiar with the 3-dimensional "rubber wall" tunnel at Göttingen know that they do excellent work there. No reason to doubt that this is also going to work.

We have, certainly, time for questions.

(Pointing to David Wigley) David Wigley.

David Wigley

Perhaps I missed some of the detail, but can you give us a little bit more detail on how you feed the nitrogen into the tube to charge it? Is it literally just through one pipe at the end, as you show in figure 4, or have you got injectors all the way down the tube?

Hefer

(Referring to a sketch of the tunnel) It's no more up to date. This picture is not the last one any more.

Here you can see a feeding ring. This distributes the nitrogen to another feeding ring. And from this ring it is injected to the tube. But we will cancel the first feeding ring now and do it about ... about like this. Increase the height of this flange and then get in by a tube. And then there will be a ring inside, in this flange, which distributes the nitrogen around the tube. And then there will be holes down here so that the nitrogen can flow this way.

This corner has been installed in order not to have too long a sliding way for this cylinder. So the nitrogen is fed in going around the tube by the ring.

Wigley

But when you're pressurizing the tube with gas, you just put it in one place and it sort of feeds ... flows back into the tube.

What I was thinking about was how you're going to establish a constant temperature along this very long tube.

Hefer

Well, O.K. I've got your point.

Here is the feeding ring and this closed loop will provide a constant temperature along the tube. So there is another tube that's 200 mm in diameter ... that's a pretty large tube ... which transports the gas back to a radial blower, here, and then a liquid nitrogen injection device, here, and then back to the fill line. So that's the circuit.

A closed circuit. The same as here, a closed circuit for the test section for conditioning of the model.

Wolfgang Lorenz-Meyer

Does that mean that the nitrogen in the tube is always in motion during the injection?

Hefer

Right. Right.

Lorenz-Meyer

There is always slight motion.

Hefer

During this five to ten minutes of charging time, it's in motion. And the velocity will be about half a metre per second.

Ralph Scurlock

Have you made any calculations as to what the vertical temperature gradient in the charge tube will be during this injection, because I'm ...

Hefer

No. I'm sorry not. I guess that will be a very hard thing to do.

Scurlock

Sure. The problem ... if you can't get uniform temperature vertically ...

Hefer

Right. We have discussed this problem, of course, many many times, and we try to cope with it by blowing in, in a spiral, you know, not radial, so that the gas can turn in the tube. The problem with this is ... this is basically very easy to do ... but the problem is that this rotation may remain inside the tube and that you run into problems during your measurement if you have the rotation in there.

So you must be careful and be sure that this rotation is small enough not to result in a rotation in the test section. Or, wait a little bit so that it ... but, in such a tube, the damping properties are very very weak. That's really a big problem. We'll build in a sort of damping plate at the end. Because otherwise, waves will move back and forth for a very long time in such a tube. For minutes, and more. And we'll build in a plate with holes, many holes, as a damping plate at the end of the tube, to damp out any ... not any, but most of the disturbances.

Kilgore

What is the insulation thickness of the tube?

Hefer

The insulation will consist of one layer of mineral wool ... that's the inner layer ... and one layer of polystyrene, and the whole thickness will be 200 mm. And we will purge the insulation along the whole tube.

(Referring to the test section region) The insulation for this part is not yet designed. But we will try out how to do that properly when the tunnel is there and you can see best how to do that.

But the long tube will be insulated by a company. And we'll put in nitrogen at this place and let it out at the end without any conducting devices, you know, like little tubes or something like that. So we put it under overpressure, the whole insulation will have an overpressure of some millibars. So that we have a very slow flow through ... at least through the mineral wool part, the inner part.

Pat Clark

I didn't understand your model temperature pre-conditioning. You said that you have the gate valve there so that you can hold the section between the gate valve and the control valve and the remainder of the tube at different temperatures. But as soon as you start the run, do you still not get the temperature diffracted in the air so that your model then would be hotter than the air flowing past it ... or the nitrogen flowing past it?

Hefer

You must provide different temperatures in the test section, for the model temperature must be different from the charge temperature in the tube before the run. And this is achieved by putting the cold nitrogen in here, in the sidewall ...

You know, one more problem is the warping of the sidewall. If the outer wall is warmer than the inner wall, for instance.

So we'll put in the gas at this point, and then have it flow back through the sidewall space to the end of the test section where the slots are for the pressure equalization device. And then the gas flows back along the model in the inner part of the test section along the model, cools down the model, and is taken out at this part here at the boundary-layer bleed off system. So that's the way of the cooling circuit inside the test section and nozzle.

Well, this temperature has to be adjusted according to the recovery temperature, or stagnation temperature, or whatever temperature you want. If you want to investigate adiabatic wall effects ... or nonadiabatic wall effects, you can precondition the whole area by a higher temperature, for instance, or a lower temperature, than the recovery temperature will be.

Clark

During the run, is it only nitrogen that was to the left of the gate valve that's close by the nozzle ...

Hefer

Right. It's all nitrogen in there. It's no air.

Clark

So, what you'd do if you wanted adiabatic wall, you would cool the test section part to the delta T you showed on your figure 2.

Hefer

Right.

Clark

You'd have it that many degrees below ... And during the steady part of the run, it would also see nitrogen at that temperature.

Hefer

Exactly. For the temperature does not change during the run. Except ...

Clark

During the starting transient you get that temperature diffraction.

Hefer

... for this gas which is trapped in the test section, here, and is accelerated so the temperature of this gas will reduce a little bit too. But that's very little.

Unidentified speaker

(Unintelligible comment)

Hefer

I didn't ...

Unidentified speaker

The model, for instance. Do you intend to measure pressure?

Hefer

Right. We need fast response pressure transducers, of course. We have some experiences with Ludwieg tube wind tunnels and we consider this not to be a major problem of the facility because it's easily done at Göttingen to measure run times of 300 milliseconds ... three tenths of a second ... to do pressure measurements about the same distance of the tubes to the outside, for instance. You can just take the same models as in the 0.3-metre and go outside with ... But then you have to have pressure transducers, not scanners, of course, to take the data at one time.

Kilgore

That was a five second pause which is an invitation to lunch.

Oh! I'm sorry. There was another question. I'm sorry.

Viehweger

What is the diameter of the tube?

Hefer

The diameter of the tube ... the main tube is 0.8 metres.

Viehweger

And what's the criteria for the decision for the size?

Hefer

The criteria for the decision for the time?

I can easily say it was the longest stretch we had. So it turns out to be a time of 1 second. I will agree to that. That's a compromise, in any case. We tried to have as long a time as possible, and we asked our measurement people, like Mr. Bütefisch, and so on, what he needs to have. And he says he needs to have less than that. But I was a little bit stubborn and said we take the longest we had ... we can get. Otherwise, we would have built a tunnel with say two thirds of the time, or so.

Kilgore

And the diameter was set by the budget.

Hefer

The diameter ... I would have rather liked to have had a larger diameter. But from experiences with the other Ludwieg tubes, it's not necessary to have contraction ratios like an ordinary tunnel has, like 12 or something like that, but it's enough to have

three to four. And this has 3.6. And if you look at prices for valves and so on, you will see that they are all moderate as long as you stay below a diameter of 600 ... 700 [mm] and then it goes up and goes up very quickly. And this is one of the reasons we took the highest we could afford at all. And, well, maybe it would have been better to take 700 instead of 800 mm.

Kilgore

Thank you, again.

Discussion following Lecture No. 11 (G. Viehweger)

Jean Christophe

(The first part of the question was not recorded.) ... minimum value and maximum value for the test, the run? What is the maximum value and minimum value of tests of a profile do you expect?

Viehweger

Excuse me. I didn't understand. Maximum and minimum ...

Kilgore

How many runs do you ... am I interpreting you right?

Stan Griffin

What's the duration of the run?

Viehweger

The duration of the run?

Christophe

The duration of the run? We wish minimum value and maximum value.

Viehweger

O.K. Yes. We have calculated a run-up time for the tunnel. You ... I think you'll see we have a problem to increase the mass flux inside the tunnel. And we have calculated the run-up time of the tunnel up to maximum velocity of about 4 minutes. And a run time for one polar between 6 or 10 minutes depending on the angle range. And we are able to have a lot of runs, one behind the other. If, for example, only to change the velocity during a measuring period. But, in normal case, we have a run-up time of 4 minutes, a testing time of about 6 to 10 minutes, and a run-down time of about 4 minutes for one run. But we can have several runs, one after another.

The time to cool down the tunnel ... I think that's another question you are interested in ... is about 5 to 6 hours. But after time of 5 to 6 hours, we have only steady state temperature conditions inside the tunnel. That means in the metal parts and the wooden cover but not in the insulation. But after this time we can start testing.

Unidentified speaker

When you bring up the pressure ... You said the equilibrium is made at the test section. Is it a dynamic or functional equilibrium or a physical connection between the inside of the tunnel and the outside?

Viehweger

Yes. We measure the static pressure on both sides of the tunnel, inside the test section and in the testing room. And we have to control our tunnel very carefully because the structure of the tunnel ... it doesn't stand higher stresses.

Kilgore

Let me let you direct the question traffic. I see Ron Law with a question.

Ron Law

Can you be absolutely sure that if there is any flooding in the floor of it (?) that the nitrogen can not get through and dampen

Viehweger

Please, can you speak a bit louder?

Law

Can you be absolutely sure that e vapor barrier will protect the concrete from the cold gas or from any liquid that may land on the floor? It will probably only have to happen once, really, to do serious damage to the concrete. Can you be sure that that cannot happen?

Viehweger

The vapor barrier has been considered very carefully. And we hope it will work very good. No one is sure.

(Laughter)

Kilgore

I might say that we have had problems in our tunnel ... in the small 0.3 metre tunnel ... in almost filling it with liquid nitrogen. And as Mike Goodyer implied, that's a very good way to control temperature, but not very good if the liquid level rises, perhaps, to the level of the fan. And, quite simply, we've found that we must have temperature sensors that automatically, first sound an alarm and then shut the tunnel down ... turn the liquid nitrogen off and shut the tunnel down ... if the liquid level rises. And I would assume the same is, or could be, used in the KKK or any other tunnel.

Unidentified speaker

Do you have temperature sensors or do you have some kind of liquid nitrogen sensor?

Kilgore

In our case it's simply ... well, they're one and the same, I would think. It detects ... It's set to trigger at approximately liquid nitrogen temperature.

Ralph Scurlock

Could I make a comment about the use of a concrete shell for a wind tunnel?

Can I ask how thick is the concrete shell ... the original concrete shell?

Viehweger

The concrete shell has a thickness between 12 and 16 cm. In the high speed diffuser, there we have 12 cm, for example. At the end of the second quick diffuser in the second cross leg it is 16 cm.

Scurlock

What I would like to say is that in designing the insulation to line the inside of the concrete, I think the intention of the insulation should be to prevent the naught degree centigrade isotherm from penetrating the concrete under any operation. And the thought of liquid nitrogen flooding ...

Kilgore

(Speaking to Ralph) "Bathing" is a good word there. "Bathing."

Scurlock

... swishing about at the bottom of the tunnel fills me with horror. Because our present understanding of concrete is that if it is exposed to thermal cycling below naught degrees centigrade ... that's this sort of conventional concrete ... it will lead to deterioration in the properties of the concrete ... eventually. Now I would say that in operating your tunnel ... you must ensure exactly the concrete at the base of your ducts ... must remain at a temperature above naught degrees centigrade on the inside wall.

Viehweger

Yes.

The thickness of the insulation is calculated ... or has been designed for a maximum temperature gradient through the wall of the concrete of no more than 1 K.

Unidentified speaker

Yesterday we saw that in T2 the temperature can be lowered from ambient to cryogenic conditions in order of 10 seconds and just a few moments ago you said 5 hours.

Viehweger

Yes.

Unidentified speaker

What ... Which parts or which (?) prevents you from lowering your temperature in say 1 minute or ... ?

Viehweger

In 1 minute?

Unidentified speaker

Yes.

Viehweger

(Laughter)

Unidentified speaker

Why not?

Viehweger

You must see our tunnel has very high dimensions in relation to T2. We have dimensions up to 8.5 metre and not 0.4 metre.

Unidentified speaker

Yes, but ... (?)

Viehweger

Yes. But we have to see that we get not any temperature ... too big temperature gradients in vertical directions in the bigger parts, for example, in the corner vanes or in our fan. With this big temperature gradient we will get very high stresses in those parts. And we must avoid it.

Kilgore

I might add a comment to that. I guess in making calculations, we do our best. And I'm sure Dr. Viehweger did better than we did for the 0.3-m tunnel. But our engineering group at Langley told us that we would perhaps have a 4 hour cool down for the small 0.3 metre tunnel.

In fact, after deciding that some components were going to break anyway ... that did need to be replaced anyway, as Dr. Wigley mentioned ... we have a 20 minute cooldown. It may be, upon suitable instrumentation and suitable measurement, that 4 hours decreases. It may be that it increases. But certainly, 4 hours sounds like a conservative start when you don't want to break it during your first cold run.

I think Stan Griffin has a question.

Stan Griffin

O.K. Can I confirm that the length of time ... or the minimum length of time that it takes to make a model change. It takes 4 minutes to go down, 30 minutes for the conditioning room, and 4 minutes to go back up again, plus the model change.

Viehweger

Thirty minutes in the conditioning room only in one direction.

Griffin

In what?

<u>Viehweger</u>

In one direction.

<u>Griffin</u>

Then it's 30 minutes to go back again.

<u>Viehweger</u>

No. I think we must have about 1 hour. We go down from the test section to the lock and we shift over in the model conditioning room, then we must have a time of about 20 or 30 hours to warm up the model.

<u>Wigley, Griffin, and others</u>

Minutes!

<u>Viehweger</u>

Minutes. Then we must handle the model. Then we go back in the same time in the other direction.

<u>Griffin</u>

So, for the minimum model change then, it's something like an hour and a half?

<u>Viehweger</u>

Yes. You are right.

<u>Unidentified speaker</u>

Would you give some details how you intend to purge the circuit from humidity. You've got wood and ...

<u>Viehweger</u>

Inside the tunnel? Yes.

O.K. You start very carefully.

Before cooling down the tunnel, we intend to blow in, at first, dry compressed air. It will be ... We intend to pressurize the tunnel in the range it is allowed, here, our tunnel ... for 100 times, for example. We'll pressurize and blow out. And we do it for about 100 times. And then, the humidity in our tunnel, we hope, is very small.

Then we'll blow in warm GN_2. And after this time, we will blow in LN_2 to cool down the tunnel.

You must be very careful. Because you have, for example, humidity in the holes between the wooden panel's insulation.

<u>Scurlock</u>

As far as access to the model is concerned, why don't we persuade NASA to build a cryogenic space suit ... that someone can go in the tunnel and save all this cooldown — warmup procedure ...

<u>Kilgore</u>

We'll describe that in five years.

(Laughter)

<u>John Wendt</u>

Did I understand you to say that on the wooden covers inside the tunnel ... there are many holes in these covers?

<u>Viehweger</u>

Yes.

<u>Wendt</u>

Do you think this will have any noticeable effect on the turbulence level?

Viehweger

No. No. The perforation in the wooden cover is very, very small. With only holes of a diameter of 5 or 6 mm. I think we have a very, good quality ... turbulence quality, inside the tunnel.

That is an informal comment.

Unidentified speaker

How do you propose an ambient test? I think you do not have a water cooler. How do you take the fan heat out if you do all (?) your calibration at ambient temperature?

Viehweger

Yes. That's a good question.

The run time will be very short.

(Laughter)

Unidentified speaker

You let the tunnel drift in temperature.

Viehweger

Excuse me?

Unidentified speaker

The tunnel is drifting in temperature.

Viehweger

Yes.

Kilgore

Last chance for questions.

Thank you, again.

Discussion following Lecture No. 12 (J. Tizard)

Kilgore

Thank you, John.

We are now open to any questions. John, you just field them from your position.

Tizard

There's none.

Kilgore

There must be a question.

Unidentified speaker

Which pressure has been designed for the LN_2 tank?

Tizard

Sorry?

Unidentified speaker

Which pressure has been designed for the LN_2 tank?

Tizard

The pressurized tank?

Unidentified speaker

Yes.

Tizard

It's ... (?) approximately 11.5 bar. The pressurized tank. The main LN_2 reservoir tank is somewhat slightly over atmospheric pressure.

The pressurized run tank provides the main driving force for injecting the liquid nitrogen into the tunnel.

[Long pause]

They're all hungry.

Kilgore

You may have to ask a question because the food may not be ready.

(Laughter)

Stan Griffin

I can always ask one.

Kilgore

O.K.

Griffin

I'm interested in the concept of alternate configurations, particularly, inserting essentially separate configurations, preparing one while you test the other one. Obviously that should improve productivity. I'm not quite sure how you k[illegible]ep the data separate from one customer to anothe[illegible] one. I'm assuming your talking about separate customers, not ider[illegible]al models. Is that right?

Tizard

Well, it could be both if the customer was willing to have two models. We could prepare two models for a similar configuration. Of course, it could be separate models and different customers. The design of the facility is that all data will be treated in confidence. There are different areas where the data analysis would be done. There's various data analysis and data reduction capabilities in the tunnel. There's more than one area where people would work.

Griffin

But isn't it true, from a productivity point of view, that would be very advantageous.

Tizard

Yes. It would be advantageous. I'm not quite sure just what the productivity of the tunnel will be. You know, we have the requirement for 5000 polars per year. And, again, we could do more tests if there's a requirement to do it. Or, if there was an urgency on two different models, and you could get agreement between customers as to who was going to run first.

Kilgore

O.K. With that, thank you again, and we will simply mill about until the food is ready, looking hungry. Maybe it'll get ready quicker.

Discussion following Lecture No. 13 (R. Kilgore)

Kilgore

We're early again.

Ralph, surely you have a question.

Ralph Scurlock

I've only got one thing to say and that was regarding your missing cryogenic safety manual ...

If anyone would like to order some safety manuals, I'll put a piece of paper down on the bench there and you can put your names on. And I'll promise to pass the orders on for attention in England when I get back.

Kilgore

Put my name down, Ralph. I need one now.

(Laughter)

I would take this opportunity, again, to call your attention to the bibliography on cryogenic tunnels and to the fact that it does have a subject index in the back. So things that you're interested in specifically, such as the work on real-gas effects or condensation, simply go to the back, take a look, see what papers are available, and then, if there's no other way to get the papers ... and usually there're other ways ... but if there's no other way, feel very free to drop me a line and say "I'd like to have that."

We're perhaps the only ... well, we're one of the few Branches within NASA that has a full time librarian who's dedicated to having archives and storing this kind of information and making it available to anyone who asks. So, we would be very happy to provide material that you can get through no other source easily.

Yes.

M.G. Rao

Did you not get any absorption effects on the model?

Kilgore

Absorption?

Rao

Absorption effects on the model.

Kilgore

No.

Rao

There could be selective absorption.

Kilgore

I'm not even sure if I saw it I'd know it. So ... I didn't notice anything.

Rao

There'd be a few monolayers of nitrogen absorbed on the model itself. Depending on the test condition. It could be selective.

Kilgore

In terms of gases other than nitrogen, or ... Perhaps I'm not clear on the question.

Rao

There could be some monolayers of nitrogen absorbed on the model ...

Kilgore

Yes.

Rao

... depending on the test condition. (Unintelligible) ... around the model.

Kilgore

How thick might these layers be?

Rao

A few monolayers.

Wigley

Many orders of magnitude less than the surface roughness.

Kilgore

Yes. That's what I was thinking. When we finally get down and stick one of our models under Dave Wigley's microscope, we don't see a lot ... except big cracks ...

Pardon?

Rao

Once the model is warmed up all this would have gone.

Kilgore

Yes.

We have had problems with some of the models where various manufacturing techniques have been used, and certain solutions, used either in soldering or in machining, or what have you... those oils or whatever, coming out and freezing around the orifices. But I think, as Dr. Wigley is saying, probably, the layers that might adhere are so small, compared to the actual roughness that we live with, as to be insignificant. Not sure, but seems to be.

Yes, Ralph.

Ralph Scurlock

Have you had any experience with flow visualization techniques? Or thought about it?

Kilgore

Yes.

Again, if you look in the bibliography, you'll see "flow visualization."

Nothing that I'd want to brag about. And certainly nothing that I'd want to bring a video tape of, because, primarily, we've had embarrassing problems at the interface between the cold tunnel and the warm real world, where we keep flow ... the ... some of the observing equipment. And, again, it's one of these areas where once you choose to address the problem, you can solve it. But, we ... "we" meaning my Branch ... we haven't chosen to go full bore and fix it so that the windows are always clear.

There is a phenomena that has appeared which is quite interesting. Depending upon the order of testing, you can get liquid nitrogen condensing inside the plenum and washing down over the inside of the windows. If you go very cold, and get everything cooled down, and then warm up a bit and do a bit of pressurization, the metal is cold enough to condense the nitrogen and then you say, "My goodness. What is this? Flow going from top to bottom." And it really is. It's the liquid nitrogen condensing inside the plenum and flowing ... mostly straight down ... over the observation window.

O.K. I'll put on another hat and say that's long enough without a question. Let's have coffee.

Thank you.

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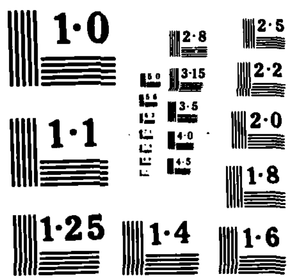
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Discussion following Lecture No. 14 (W.E. Bruce)

(The first question and a portion of the response were not recorded.)

Bruce

... and the part recaptured back to the initial point ... to take them back out and put them in ... so we're talking something like 2 hours, plus whatever work you want to do to the model. And that's all using the access tubes.

Unidentified speaker

Do you plan to sometime depressurize the plenum ... (unintelligible) instead of putting the gate valves in place?

Bruce

Oh, yes. That's an option ... That's an option we've been working on. The decision was made by our management people here, some time ago, when we had problems with ... I was telling you about the gate valves ... we had to rework the heaters on them ... was, just leave them alone and we'll go ahead and use the access tubes. We'll just vent the whole tunnel down to atmosphere. And, it doesn't really affect productivity. It effects only cost because your wasting part of that nitrogen. The productivity is bound to be some time there to get it back to pressure. But, it doesn't take long.

Unidentified speaker

Don't you save the 20 minutes that it takes to move the gate valve?

Bruce

You can save that. That's true. You can save that. But that's the way we went early when we made our decision.

But, we've had another problem on that 9 by 12 door that precluded us from really using the access tubes until just recently.

There's one thing I mentioned when I showed you the insulation. I showed you those buckets of nails up there. And even though we thought we had the tunnel cleaned up, when we started running, they were some of the things that hit the fan blades and went through it. Nails.

I mentioned drill bits that were left in there. We don't know where they came from. We could never find them. But they came out and we picked up some drill bits, and scissors. They were somewhere behind this aluminum liner that we didn't get to, I guess, to start with. But it put a good test on the fan blades.

(Laughter)

Kilgore

O.K.

Thank you, again, Ed.

Discussion following Lecture No. 15 (W.E. Bruce)

Kilgore

We certainly have time for questions. And, Ed, I'll let you field them from your position. You can see better than I.

Bruce

Yes.

Pat Clark

Ed, on those pressure ratio curves you showed in the beginning ... figures 3 and 5 ... you said that your theoretical values there had come from work that was done earlier. Is that given in reference 3, the (?)

Bruce

Let's see. You're talking about the operating envelope pressure boundaries ... pressure ratios?

Clark

The fan performance. The pressure ratio — Mach number curves ...

Bruce

There's a reference in there by Blair Gloss and Nystrom, I think. In the report ... do you see that? Or ... Nystrom.

Clark

No, I don't.

Unidentified speaker

Oh, yes. 13.

Kilgore

Yes.

Bruce

Reference 13.

I might also point out ... I didn't mention it at the time ... but the instrumentation that we have on the model dealing with the balance, and the model deformation system I referred to, and the ESP system, and this laser AOA system, are documented there in that reference 15 that I have on my list. That was a 1982 publication, but it does give some of the challenges they had for competing with the cold environment, and their approach, and what they were doing. And that's still valid today, for this is really the first time we've been back to get actual data and see how everything's performing.

And I know that some of their data and results are going to be published at the ... I've got it here ... the 31st International Instrumentation Symposium, ... *that's the* Instrumentation Society of America ... May 6-9, 1985. I know they've got ... in fact, I've got rough drafts of their reports on the ESP system ... there're going to present that ... and the model deformation system will be presented at that conference. You'll have to excuse me.

Pat Clark

One other question. You mentioned that the data that had been predicted earlier, I guess in reference 13, had been adjusted for higher heat exchanger losses than had been originally assumed.

Bruce

Yes.

Clark

Do you know, off hand, what the range of loss factors you have across the heat exchanger? What your final values were?

Bruce

Earlier ... I'm not sure I can give you the exact numbers. Earlier, we were looking for this cooling coil to have like a maximum loss across it ... in terms of delta p over q ... of like 5. And we said anywhere in the range of 3 to 5 would be ideal. We didn't want to get too low on it because that's required, you know, for the back pressure on that rapid diffuser we've got. So we had set a goal to be between 3 and 5. As it actually turns out ... and we knew this before we got around to running the NTF due to some of the follow on studies that we did in Bob's 0.3-m cryo tunnel ... it turned out that at high Reynolds number it came in at about 10 or 11, somewhere in that range. I've got the data but I don't have it with me.

Clark

So they ... You say at the high Reynolds number it was around 10 or 11. At lower Reynolds numbers it would be a bit higher?

Bruce

It would be higher. It's like an exponential curve that comes down and flattens out with Reynolds number.

Clark

Thank you.

Bruce

Yes?

Unidentified speaker

How much time do you spend to stabilize the temperature condition for your balance? And can you say anything about your temperature accuracy?

Bruce

As far as temperature stabilizing ... What we've been doing to date for the calibration parts is spend a lot of time, I guess, making sure the tunnel is at temperature. If we're going down to 115 K to run, and we set there quite a while until everything is stabilized out. That's just the way it's turned out to date. We haven't really looked at it as to what we could get by with in minimum time yet.

We do have thermocouples on the balance and we're looking at those all the time, you know, and when we more or less get to steady state conditions, that delta T between the thermocouple and the outside of the model is pretty close to zero. You see, I don't have numbers to tell you how long it takes it to stabilize, though.

The accuracy on the ... your talking about the balance ... it's something like a quarter of a percent. In that range. We do make some temperature compensation in our software program for the balance. I'm told by our Instrument Research Division that if we didn't make the temperature compensation, that the balance would probably turn out to be totally within a half percent accuracy. And then, by making the temperature corrections to it, it puts it down somewhere in the range of a quarter of a percent.

Any other questions? Yes.

Wolfgang Lorenz-Meyer

You show the Pathfinder and Orbiter model on sting mounting. This sting looks very thick. My question is for what stagnation pressure have those stings been designed?

Bruce

What stagnation pressures have the stings been designed for?

Lorenz-Meyer

Yes.

Bruce

They've been designed ... most of them ... for what we call high q loading, which goes with the high stagnation pressure. It all depends on what the model load would be that we put on it. That particular one that we have with the Pathfinder, there, it would take any load that Pathfinder would put on it for the tunnel conditions, for actually, the Pathfinder happens to be the limiting thing there. The configuration we have on the Pathfinder would not go to the maximum conditions in the tunnel.

We've got stings that are designed to go all the way up to 7000 psf free stream in the tunnel. They'll take normal force of 20,000 pounds ... the prediction. I don't know the actual number (unintelligible)

(Considerable background noise here due to high-pressure water jet cleaning of the building.)

Yes?

S. Luck

In your figures 7 and 8 ... the performance maps for the NTF. Will you tell me why the power limit is a discontinuous curve?

Bruce

On figure 7 and 8, why the power limit is a continuous curve?

Luck

Discontinuous.

Bruce

Excuse me. Maybe I didn't understand. Why the power limit ...

Luck

Why is it a discontinuous curve?

Bruce

Well, O.K. Your looking up there at the top where it's got like 93 megawatts coming across it? Like ... that's a continuous curve coming down across the top. We've just cut it where the pressure intersects it ... Is that what you're looking at? ... and where the temperature intersects it.

Luck

Why do you go down line of constant temperature? Is that a limit to the boundary?

Why, if that 93 megawatt line continues, why does it suddenly go down the isotherm?

Bruce

Well, it doesn't. Lets see. If you draw it on across there it's a curve that just goes right on across the page. Does that make sense?

(Goes to board and draws typical performance map)

If you draw that power curve on there, it goes like this ... coming down. We've just chopped it right there and there and it hits all those boundaries.

Luck

But why? Why is the boundary now given by the 160 degree kelvin isotherm?

Bruce

Why does it change here then? Like that?

Luck

Yes.

Bruce

That has to do with the ... Let's see. It's a combination between our fan performance system. It has to do with the IGV system as far as angle range ... which you can think of like pitch on the fan blades ... and the condition that the fan has to run in in order to get to the top part. At the top part of the envelope ... to get above ... to get above where you see this little dip right here ... this little dip ... to get on up in there, you have to use all three motors and the shaft runs at constant RPM. And with it running at constant RPM, and the IGV as far out as it will go, that's as far as it will go that way. Now, to get on this one over here, you have to start increasing fan speed to get it on up. And we just don't have the horsepower to do that with since one of the motors has to be a synchronous speed motor.

Luck

So that long (unintelligible) line is 93 megawatts?

Bruce

Well, this is 93 running across here. And as you come down this way on that boundary, the power drops till you get down to here, and now this is the capability of the other two motors that we've got that have variable speed capability, and then we can pick up and push that boundary on back over in here ... with the variable speed.

But the horsepower curves are going across there.

I don't know if that answers your question or not.

Unidentified speaker

(Unintelligible comment)

Bruce

Excuse me?

Kilgore

Is it an experimental line?

Bruce

You can go back again to the fan performance maps that were done earlier by Gloss and Nystrom, that's referenced in there, and they predicted these boundaries. And then the only thing that we have done is gone back and verified it with experimental data. The operating envelope matches up very good except this curve here ... that part moved up like to that. That moved primarily because of the higher pressure ratio in the tunnel circuit.

And our fan performance ... IGV system is not performing exactly at the high end ... power end ... as earlier predicted. And so, that means we lost that little part from there unless we come back and do something to the fan or the IGV system, which I don't think we're going to do anything to right now because we really haven't lost that much. So we ... the experimental part that I'm showing you in my figures is this boundary right there.

One in the back.

Unidentified speaker

The last slide ... I had the impression that the slot width of the slotted bottom wall was not constant. Is this impression right? Are the slots tapered or are they of constant width? Perhaps we can have the last slide?

Bruce

The last slide was the flow angularity slide.

Unidentified speaker

No. This one.

Bruce

O.K. That one would have been what, figure 8? Where it went ... 0.8 Mach number?

Excuse me? What was the question again. I'm not sure I understood.

Unidentified speaker

My impression is that the slot width is not constant along the whole length of the test section. It's much narrower below the model and in the beginning it's wider. Is this a wrong impression or is the slot tailored?

Bruce

It's tailored. It's not constant throughout the test section. You're talking about these slots right here?

Unidentified speaker

Yes.

Bruce

They've got a certain configuration to them based on experience at Langley from their 8-foot tunnel facility that's got slots in them that this test section is more or less patterned after using a slotted test section wall. And our aerodynamic people that were familiar with that and the calibration of it designed and laid out these slots. And you're right, they're not a constant width.

Unidentified speaker

Is there any detailed information in the references you gave on that project?

Bruce

There's nothing published as far as slot dimensions that we've got here. Let's see, Bob, do you know if ...

Kilgore

I don't think the data's published. It was done, as I recall, by Ramaswami and one other chap [Cornett] ... and Bill Igoe was involved. I don't know of a reference on that. That doesn't mean there isn't one. The likelihood of there being one though, I think, is fairly slim.

Bruce

Fairly slim. Let's see. If there's anything in the test section that we've sort of been sensitive to ... and that's giving people dimensions on our slots. I don't know why ... but that's sort of a special developed thing ... but, I don't know of anything hidden about it either. You know, we could probably ...

Kilgore

I think ... you know ... if you would leave name and address and query, we would certainly attempt to see if there was something published. I don't think either Ed or I could guarantee to send you anything. But, if there's something that's available, we would certainly get it to you.

Bruce

While you're talking about the slots, that's one thing that Langley is proud of. I guess back in the early 50's they came up with this test section slot configuration for transonic testing. I guess around the early 1950's they won a Collier's Trophy award on that configuration ... which is a pretty high award in the United States for the aerodynamic field.

Are there any other questions?

Unidentified speaker

Do you adjust the walls for temperature or do you choose a mean setting for all the operating envelope?

Bruce

The walls ... like the top and bottom walls?

Unidentified speaker

Yes.

Bruce

We will adjust them as far as the ... we'll adjust them and it will probably turn out to be a function of Mach number, I guess, more than anything else when we get through. And that's a part of it we'll put back into our computer system that when we're on the Mach number it will automatically adjust them then. These walls also are controlled by a closed loop system. It's a slow operating system since there're motors and a jack screw.

I expect what's going to happen ... a trend that's been in the past ... they'll probably remain at a fixed position at low Mach numbers and when you get up to be transonic, it probably takes a different configuration ... at the upper Mach numbers.

Yes?

Unidentified speaker

Have you measured the flow temperature distribution near the wall or only in the center part of the test section?

Bruce

No. We have not done that as of today. We do have a ... We will be measuring near the wall and we have wall survey rakes ... you know, that stand up ... that's to be mounted out some of these windows. That's one of the things we're thinking about putting in now when we go back into operation, as well as looking at pressure distribution near the wall, a lot of studies that you all have pointed out here this week on adiabatic wall temperatures on the models that will be investigated in the future. In fact, there's a person in Bob's group here that's done a lot of that type of studies.

Kilgore

Yes. I can add that in the 0.3-metre we very early on ... in fact, in support of the NTF design ... made a thermal survey of ... a survey of the thermal boundary layer in the big end of the tunnel. And we built a probe that, as I recall, was something like 5 inches from the wall, instrumented every half inch. The thermal boundary layer was within that half inch [next to the wall] and we consequently sort of said "well, there's no big thermal boundary layer," and we went on to other things. I guess we wouldn't expect to see ... because of the nature of the construction and the mode of operation ... any great difference as you approach the wall.

Bruce

Yes?

Unidentified speaker

In your figure "future plans" there's one item, "checking the high speed diffuser and measuring dynamic pressures." Do you already now have some indication that this diffuser is not working properly? Do you expect probable separation in some part of the operation range?

Bruce

We don't suspect anything. We don't have any indication, to date, you know, of anything unusual. That was sort of ... You're looking at our plans that go way back, even before we started calibrating the tunnel and running it, saying, you know, these were the plans we wanted to do, you know.

All right. One more [question].

Ron Law

How do you observe the model? Do you have T.V. cameras in the plenum or what system do you have?

Bruce

Visually observe it?

Yes. On the back side of the wall of the test section ... I think I showed you that yesterday, where we have ports and we have lights ... we also, ... to date, we've had two T.V. systems, monitor heads. They're mounted in an enclosure with heaters in them, inside insulation to keep them warm, and they also have a vent system ... they won't take pressure ... to where we bring ... well ... there's a pipeline between that and outside the tunnel to atmosphere to keep them at atmospheric pressure. And we also do have a line coming in that we can bring a purge gas ... like dry air ... to purge it out or even flow some all the time so that the heat that builds up from the electronics is picked up and taken out.

We have that ... that's the primary thing we've used to date to look at the model and the sting. T.V.'s. And they're on a gimbal where we can pitch and yaw them from the control room ... the scanner.

Kilgore

O.K., I'll take that pause to say thank you again, Ed.

One more question?

Bruce

Yes.

Kilgore

O.K. I was premature in cutting things off.

Unidentified speaker

You gave an indication of how the performance of the fan looks like with a blockage model in. If you were to check the air line also with a model with downwash ... with high lift ... what the air line and pressure ratio is doing according to this one disturbance in the test section? In terms of the tunnel flow?

Bruce

We have not done that with a model ... like the pathfinder model I was showing you here ... since we just put that in in December and we went straight on to the other two Shuttle models. We've got the data that was recorded from the instrumentation back in the fan region on one of those tests. But one of them we didn't have it hooked up. It's still on tape. It's still in raw data form. But, we have not spent the time to go back and analyze that due to the pressing need for these other two models that were essential to the program.

Kilgore

O.K. Thanks again, Ed.

Announcements and Comments Relative to the NLR Balance

R. Kilgore

Now, I have a couple of announcements. We want to get on to the coffee break.

Actually, what I want to do is to prepare for the last lecture. So, I'm rushing things a bit.

Those of you who find, or think you've found, errors in the papers, the nice thing to do would be to first call them to the attention of the author. Verify, if you can, that you really have found one. And you get some kind of award for doing this. I'm not sure what it will be.

It will be up to the authors to communicate ... and this is an announcement to the authors ... to communicate corrections directly with Bob Rollins in Paris. And he will get them incorporated in the papers.

The other thing that I want to do ... I must have had a bad day yesterday because at least two people have come up to me and said, "Bob, why do you say such bad things about the NLR balance?"

There was no intention at all on my part of saying anything bad about the NLR balance and I think I certainly must have left the wrong impression. I don't present any data on that because we haven't done the analysis and the analysis is being done and we certainly have no reason to feel that the NLR balance is inferior to any other balances that are being developed. In fact, there's the likelihood that it will be superior to other balances that have been developed. I want to set that record straight. I certainly didn't mean to imply anything with evil intent yesterday.

With that suitably said and recorded, let's go ahead and have our coffee break and then we'll come back for the last session ... guaranteed to get you out on time. Thank you.

Discussion following Lecture No. 16. (R.A. Kilgore)

Unidentified speaker

(The first part of the question was not recorded. It had to do with whether there was a cryogenic tunnel in the USSR.) ... does that mean there aren't any or you just don't know?

Kilgore

It has to be the latter. It has to be that we don't know. Mike Goodyer has received requests from Russia for various papers. They haven't written me for them because they know how our people in Headquarters would react. But, they have written Mike Goodyer asking for papers and references.

I don't think I will be divulging anything to say that several years ago I asked our CIA people to have a "quick look" over Russia to see if there were any evidences of massive exhaust plumes ... and ... this is probably off the record ... and they said "No." It would be of benefit, I think to all of us, if any of you are aware of activities outside of the NATO countries that haven't been covered ... particularly in Russia ... if you would pass on very discreetly that information. And then we would pursue it very discreetly.

We do know that the Russians ... or at least we're fairly confident that the Russians have a high Reynolds number tunnel. As I recall, the dimensions are ... well, it's a transonic tunnel ... 5 metres by 5 metres at 5 atmospheres with something like 800,000 installed horsepower. And when you move the numbers around, you find that they could perhaps get Reynolds numbers, based on a typical chord, of 36 million. And that's compared to our pre-NTF highest Reynolds number in the U.S. of about 13 million. Whether or not that explains why some of the Russian airplanes do so well, I don't know. But, we're reasonably confident that they have a high Reynolds number facility that's not cryogenic. Therefore, there may not be the drive for them to pursue cryogenic wind tunnels until they see good data and snatch good data coming out of the NTF.

Any other questions?

Yes?

M.G.Rao

Why is it always limited to liquid nitrogen?

Kilgore

It's not.

We've done a study of ... Well, it should be, for general purpose testing ... certainly where compressibility effects come in ... your gas should be limited to diatomic gases. We've done a study of hydrogen, which is a good diatomic molecule.

Unfortunately, as you go colder and colder, it loses a rotational degree of freedom and then quits acting like a good diatomic molecule.

Ralph Scurlock and his people are in fact studying other manifestations of cryogenic ... Well, you're right there. You've ask this question? Yes. This is a planted question.

(Laughter from Scurlock)

You're probably involved with a study of gaseous or liquid helium cryogenic wind tunnels. And, if, at some time, one could find a way of circulating liquid helium II, of zero viscosity ... and Ralph will tell us all the problems involved with that ... you would have infinite Reynolds number. You probably have no loads. Whether you get any data out or not, I guess, is a good question to ask. But it's an interesting concept to think of ... which brings me to a point that I like to always make.

Every 5 or 10 years, one should get out their list of problems, whatever they are, and look at their problems in the light of emerging technology. And I think it's true in terms of cryogenic wind tunnels, it's true in terms of magnetic suspension and balance systems, emerging technology in superconductivity, for example, makes it possible for us to think today in terms of suspending models in very large wind tunnels ... much larger than the NTF ... magnetically, and getting away from any problems of support interference. So, again, you've led me into a digression. But I would admonish everyone to periodically pull out your list of favorite problems and see what other people's development work has done toward their solution.

That's enough of a pause.

Summary and Perspective (R.A. Kilgore)

Kilgore

Let me attempt, now, to summarize what's gone on.

About the only notes that I have here ... before I get carried away ...

The purpose of this special course ... as you may have heard me say either at the [lunch] table or have perceived from previous statements that I've made ... is at least twofold.

It's to get all of you here looking at each other, talking to each other, assuming that you have common interest and common problems. You can look at people and decide whether they're trustworthy or not trustworthy. You can make acquaintances that you can call on and you can use the social aspect of this gathering to great advantage.

The second purpose ... and perhaps the lesser of the two ... has been to have us stand up here and repeat things that are already printed and that you could read, but to give you the opportunity to ask, in an open forum, questions.

Whether or not we've met these purposes you get to put down on a piece of paper and pass on to John Wendt.

Before I get into what I've attempted to do in terms of a summary, I think it's proper to start fairly far back with people who have made contributions to this event.

Christian Dujarric, as a member of the AGARD Fluid Dynamics Panel, early on recognized that we were beginning to come to the age of cryogenic wind tunnels and that industrial users would have concerns that should be addressed in a special course like this. And he made the proposal to the next group that should be acknowledged and recognized, the AGARD Fluid Dynamics Panel.

Bob Rollins is the Panel Executive of the Fluid Dynamics Panel and Bob has played a big behind-the-scenes role in making all of this possible.

Then we come closer to home, and we have to thank the Staff of VKI, especially John Wendt for providing ... I will leave out any thanks for the projectors ... (laughter) ... but for everything else, it was absolutely perfect.

We've discussed, John, a collection. But I don't ... I think possibly some of the research institutions represented here have surplus [slide projection] equipment that they might ship to you. I don't know. (Laughter)

But John has done a super job. I met John 5 years ago when Mike Goodyer was the director of a similar course. Mike had nothing but good vibes in his relationship with John, and I was very pleased when John agreed to be the local coordinator for this lecture series.

Moving on to other important people: Certainly the Lecturers, who, as Dave Wigley says, "devoted a considerable amount of time" to the preparation of the material.

Beyond the lecturers, though, at least in most cases, except for Dave who's sort of an independent consultant ... we all had Bosses. At least I guess all of the Lecturers have Bosses. And I was extremely pleased when with every request for someone to be allowed to make a presentation, the higher ups were enthusiastic. Total support.

I think especially in terms of the French contributions, where we started off with two lecturers ... when it became apparent that the lectures would be given in English ... they said, "well, that's going to be a little bit hard for each of two to give two lectures, let's just provide you with a couple of more lecturers." So it really has all worked out tremendously well.

Finally, the Audience is absolute essential. The early worry was that there were 10 people in the world interested in cryogenic wind tunnels and 9 of us would be giving lectures. It is apparent that there are more than 10 people interested in cryogenic wind tunnels. So you're to be thanked for your attendance and your participation in terms of questions and discussions, especially.

This is my favorite vu-graph of all times. Otto Lilienthal, who was an inspiration to many people, but most importantly, was an inspiration to the Wright Brothers, said ... and this is a free translation, I gather,

> *It is easy to invent a flying machine;*
> *more difficult to build one;*
> *to make it fly is everything.*

He was an inspiration to the Wright Brothers. They not only built one, but they made it fly.

And in your mind's eye I want you to ... the next time you're on any big airplane, whether it's Concorde or L-1011, whatever ... whatever you're on and whatever you're happy with, think that this happened only 82 years ago. And think that they were eaten by mosquitoes on the east coast of North Carolina. And they were frozen, and they did all kinds of strange things in order to make this work. And then see how far airplanes have gone in 82 years.

Now, in order to try to bring it a little closer to what this is all about, and to summarize what we've done ...
In 1920, wind tunnels had been in existence roughly 50 years. But they still had problems because they were being pushed to higher and higher speeds. Their problems were:

> Low Reynolds number
> Flow unsteadiness
> Wall interference
> Support interference

We've been here talking about the solution ... and apparently the only acceptable solution ... to the first of these problems.

Now remember how long it's taken to get us to being comfortable flying across the Atlantic. We've had the wind tunnel technology since 1870. Cryogenic technology since ... Ralph could probably add or subtract a year or two to that ... somewhere in the order of 1877. We've had cryogenic wind tunnel technology for 14 years.

And looking at the NTF, looking at the design for ETW, looking at KKK, looking at all of the other projects, we're making progress, but certainly, we're in the early days.

I want to make a prediction that every concern that an intelligent group like this chooses to address, every problem that you choose to solve, will in fact be solved. There is no reason to think otherwise. If the internal combustion engine can be made to run 100,000 miles, anything is possible.

In terms of what a cryogenic wind tunnel can do, we've realized a few benefits beyond what we set out to realize. You can achieve full scale Reynolds number in a tunnel of reasonable size, reasonable dynamic pressure, and reasonable levels of drive power.

Furthermore, ... and in some cases, more important ... you're able now, for the first time ever, with a single test set up, with a pressurized cryogenic tunnel, to separate the effects of Reynolds number and Mach number and aeroelasticity.

The implications are tremendous in terms of advancement in test technique. The least we should accept is the ability to do in cryogenic wind tunnels what we do in ambient temperature tunnels with the added dimension of full scale Reynolds number. It's up to us to move beyond that point and find other applications ... such as they've done at the University of Illinois ... other uses for cryogenic wind tunnels. Certainly, there must be some.

(Referring to slide)

You heard Ed Bruce mention Langley's award for slotted wall tunnels. There probably can be some arguments as to where slotted wall tunnels really came from. Back in 1870, we had the first wind tunnel. Not 1871. It took up until 1916 to close the circuit. Max Munk came up with the variable density tunnel. The first full scale tunnel came along in 1931. And it's obvious ... You can tell where I'm from because NACA and NASA are prominent through all of this. The low turbulence tunnel was built in 1941. The slotted tunnel came along in about 1950. And cryogenic tunnels in 1971.

And what do we have to look forward to in the future? ... is indicated by a couple of boxes up there. Reflect back to the problems of wall interference and support interference and then imagine adaptive wall tunnels eliminating the wall interference and magnetic suspension eliminating the support interference. So what do we have to look forward to?

Certainly, based on what we've heard here, we will have wind tunnels that will give us the proper Reynolds number. Certainly, based on the work that's going on in other fields, that you haven't heard too much about, we will eliminate or greatly reduce the effects of flow unsteadiness and wall interference and support interference.

So life is better looking in the future than in the past, somewhat akin to the contrast that you see between the Wright Flyer of 1903 and the trans-Atlantic airplanes, up to and including the Concorde. We are in the early days of making major advancements in wind tunnels.

Tied to wind tunnels ... intimately tied these days ... are computers. And that would lead us into a whole additional week of discussion if we tried to discuss all of the good things that could happen when we combine good wind tunnel technology with present day computational capability.

I hope that you've gotten what you came for out of this Special Course. Some of us ... the lunches are so good ... we may have simply come for the good lunches. Some to renew acquaintances. Some to learn what was going on on both sides of the Atlantic or perhaps on the other side of the globe.

Whatever you came for, I hope you achieved.

Thank you.

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The Report is a collection of the lectures presented at a von Kármán Institute/AGARD Dynamics Panel Special Course on "Cryogenic Technology for Wind Tunnel Testing" presented at the von Kármán Institute, Rhode-Saint-Genèse, Belgium, 22—26 April 1985.

Following a brief review of the development and early application of cryogenic wind tunnels, the 16 lectures examine the following aspects of cryogenic wind tunnel technology related to the design and operation of cryogenic tunnels: cryogenic engineering and safety, properties of materials at cryogenic temperatures, model design requirements and fabrication techniques, instrumentation for control and data acquisition, data accuracy, productivity, and costs of models and operation. A review of the status of cryogenic wind tunnel projects is also presented.

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